NCHRP

SYNTHESIS 527

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Resilience in Transportation Planning, Engineering, Management, Policy, and Administration

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 527

Resilience in Transportation Planning, Engineering, Management, Policy, and Administration

A Synthesis of Highway Practice

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2018

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research is the most effective way to solve many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the Federal Highway Administration. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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The **Transportation Research Board** is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to increase the benefits that transportation contributes to society by providing leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied committees, task forces, and panels annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-05, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, Synthesis of Highway Practice.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Tanya M. Zwahlen
Staff Officer
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The objective of this synthesis is to document resilience efforts and how they are organized, understood, and implemented within transportation agencies' core functions and services. This information can help inform how transportation agencies approach regaining functionality after a major disruption or disaster.

The information contained in this synthesis was obtained using (1) a literature review focused on practice; (2) a survey of transportation agencies; and (3) the development of four case examples (including interviews) based on the results of the survey. These examples illustrate multijurisdictional, collaborative, and transferrable practices regarding resilience.

Aimee Flannery of Applied Engineering Management Corporation collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation.

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Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Resilience in Transportation Planning, Engineering, Management, Policy, and Administration

The objective of this synthesis study was to document resilience efforts and how they are organized, understood, and implemented within transportation agencies' core functions and services. Core functions and services include planning, engineering, construction, maintenance, operations, and administration. The information gathered details the motivations behind the policies that promote highway resilience; definitions of risk and resilience and the relationship between these two fields; and how agencies are incorporating resilience practices through project development, policy, and design.

The findings of this report reflect information gathered through three primary sources: a literature review, a survey of state DOTs, and five case examples developed through interviews with infrastructure agencies incorporating resilience into their programs. A review of national policies found that although resilience policies are becoming well established, there is a lack of integration of resilience into practice within transportation. With the recent requirements for risk-based asset management plans, it is possible that state DOTs have yet to fully complete those requirements and are struggling to address an unmandated management approach. Also lacking is strong guidance correlating a relationship between risk and resilience, which would be helpful to allow agencies to understand how their risk assessments can help support their system resilience analyses. In addition, although policy touts the need for resilient systems, the lack of monetary assessment of the value of system resilience makes it challenging for agencies to stretch limited dollars in another direction when already faced with challenges related to new performance metrics such as safety, infrastructure condition, and operational reliability. The relationship between each of these metrics and system resilience, in the transportation sector, has not yet been fully developed in an easy-to-use guidance or modeling tool to assess resilience. Because of this, implementation and understanding of performance metrics and resilience will continue to be a challenge at state DOTs.

The literature review identified shortcomings in the definition of resilience, the quantitative relationship between risk and resilience, and metrics to measure resilience. Much of the focus of resilience definitions is on the ability to recover post event; however, a Department of Homeland Security (DHS) study was reviewed that helped to define key discriminators for resilience definitions to address the full range of time periods in which resilience is needed to be focused on by asset managers and owners and reflect four goal areas (maintaining continuity of function, graceful degradation, recovery of function to desired function in designated time, and inhibit basic state of change). The reflection of definitions against the key discriminators provided by DHS for infrastructure systems may be of use to state

DOTs as they move forward with their resilience programs as a way to help identify resilient practices and policies that address a broader range of activities that can be implemented to provide more than quick recovery post event to transportation assets.

Resilience metrics also appear to be lacking in quantitative measures that can be readily calculated and assessed. Much of the published peer-reviewed literature focused on using existing operational metrics normally related to system reliability as surrogates to reflect recovery time as a measure of system resilience. Some researchers have attempted to measure characteristics such as the angle of deterioration and recovery triangles during weather events on interstate systems. This approach appears to have promise with the availability of historical traffic performance data at the micro- and meso-scales. In general, however, it appears that agencies are struggling to measure system resilience as was reflected in the state survey reviewed in chapter 4 of this report.

The survey of 40 state DOTs (80%) revealed that most respondents are working to incorporate resilience into their management programs; however, a closer look at their responses to questions related to information needed, revealed that agencies are seeking information on resilience metrics and assessment methods, criticality assessment models, asset vulnerability, and the expected benefits from mitigation measures. Given the lack of documented metrics for resilience in the literature review and the request of additional data from states on how to measure and assess resilience, this appears to be a pressing need to fully address resilience in transportation systems. It is also noted that a wide range of agency divisions responded to the survey, including asset management, operations, design, planning, emergency management, and maintenance. This range of agency divisions that are working to address resilience may imply the need for a framework to assist agencies with determining roles and responsibilities of the appropriate offices and programs within highway agencies to address resilience throughout the project life cycle.

Five case examples were developed: three for state DOTs (Arizona, Colorado, and Delaware), one for the Port Authority of New York and New Jersey, and one for the Genesee Transportation Council, a metropolitan planning organization (MPO) in the State of New York. The case examples document what each agency is doing to address resilience within their agency. The three state DOTs included in the case examples started resilience analysis at different points: Arizona DOT (ADOT) was involved in FHWA's climate change pilot programs and has focused efforts on establishing a unique relationship with the United States Geological Survey to improve their understanding of the potential flow and path of extreme rain events and how those flows may affect ADOT assets. Using this information, the agency is seeking candidate locations to apply a newly developed process to economically validate resilience investments referred to as the Resilience Investment Economic Analysis. Colorado DOT (CDOT) is building on lessons learned from the devastating 2013 flood event, which damaged over $750 million in highway assets. Using ASME's Risk Analysis and Management for Critical Asset Protection framework, CDOT is proactively conducting an all-hazards risk-and-resilience assessment of the I-70 corridor from border to border. The goals of the project include developing a repeatable process, establishing a model for assessing asset criticality, determining the most risk-prone locations on the corridor, and developing mitigation plans for some of the locations. Delaware DOT, also an FHWA climate change pilot site, has focused their efforts on incorporating resilience into their policies and planning areas. Much of their resilience assessments are focused on sea-level rise and coastal flooding, given the state has the lowest average elevation in the country and 381 miles of shoreline. The two remaining case examples were included to demonstrate how similar entities (a port authority and an MPO) are addressing resilience.

Based on the information gathered through three distinct sources of data (a literature review, state DOT surveys, and case examples), the three primary challenges for state DOTs for incorporating resilience into their management programs appear to be the following:

- A lack of understanding on how resilience is related to risk assessment and management;
- A lack of metrics to measure system resilience and the benefits expected from resilience investments; and
- A lack of clear direction as to how system resilience and mandated transportation performance measures such as safety, infrastructure health, and system operations can affect each other.

Finally, much of the information related to highway system resilience appears to be disjointed in that climate change, risk assessment, asset deterioration as reflected in asset management plans, operational performance, and safety performance have yet to be fully integrated to demonstrate how each affects the other. In addition, the lack of clear metrics to measure system resilience leaves agencies to struggle with appeasing policy makers who react to national mandates without the tools to implement resilient practices. Finally, data to support such analyses, such as the expected performance or benefit derived from mitigation measures implemented to improve system resilience, make it very difficult for agencies to justify such investments as compared to model and data-rich areas like operational or safety performance when competing from the same limited pool of funding. Simply stating that a design or maintenance activity will improve system resilience is not enough to support the argument when considering the funding allocation process when other management areas have well-established data sets, metrics, and models to forecast expected performance. National research could shed further light on addressing the integration of resilient practices into highway programs.

CHAPTER 1

Introduction

The focus of this project is on resilience in transportation planning, engineering, operations management, policy, and administration. The information details the motivations behind the policies that promote highway resilience, definitions of risk and resilience and the relationship between these two concepts, and how agencies are incorporating resilience practices through project development, policy, and design. Given the relative novelty of resilience in transportation, efforts in this report have been made to provide background information on various definitions of resilience that agencies have adopted, the relationship between risk and resilience, and how resilience is being incorporated within highway agencies.

The findings of this report reflect information gathered through three primary sources: a thorough literature review, a survey of state DOTs, and five case examples developed through interviews and traditional data gathering with infrastructure agencies incorporating resilience into their programs. A purposeful attempt was made to focus the literature review specifically on resilience and not on associated topics of risk management or climate change modeling of transportation systems, as these topics have been well documented and are not the primary focus of this study. Efforts were concentrated on reviewing and including information that has been published in peer-reviewed sources and on documenting the evolution of the concept of resilience in transportation. Equally, the primary focus of the literature review is on highway transportation, though when information was missing on a particular topic, and other modes of transportation had more information available, this information from non-highway modal areas has been included to help provide the reader with a solid foundation of that particular topic. International studies were also included when relevant and to help bolster areas of the literature that might be lacking in domestic examples. Nearly 100 sources of information were used to develop this report.

A national survey of state DOTs was conducted to supplement the literature review findings, identify applications of resilience within state DOTs, and document any challenges these agencies face when implementing their resilience practices. In addition, the survey was viewed as a screening tool to identify state DOTs that are addressing resilience and that might be interested in participating in a case example for the report. Given the lack of a home for resilience within highway agencies, the survey was sent to a range of offices, including operations, emergency management, asset management, planning, maintenance, and design. Efforts were made to identify potential survey respondents through AASHTO committee memberships, through presentations and publications made by state DOT representatives, and with the help of the NCHRP committee panel. Extensive efforts were made to increase survey participation through the identification of alternative contacts within those agencies who did not respond to the initial survey request, follow-up phone calls, and in-person delivery of requests at various conferences. In the end, 40 state DOTs participated in the survey for a response rate of 80%.

Finally, five case examples were developed to document the various activities infrastructure agencies are deploying to include resilience in their policies, planning, design standards, and maintenance activities. At the request of the project panel, efforts were made to document endeavors outside of the state DOT realm, and case examples were developed for a multimodal port and a metropolitan planning organization (MPO). The case examples include Arizona DOT (ADOT), Colorado DOT (CDOT), Delaware DOT (DelDOT), the Port Authority of New York and New Jersey (PANYNJ), and the Genesee Transportation Council (GTC) in the State of New York. The case examples capture the lessons learned from each agency with regard to resilience policy, modeling, inclusion in design standards and practice, and unique mechanisms being used to fund resilience practices.

This study used multiple methods to gather information related to the use of resilient practices in highway systems, including the following:

- A literature review of state, local, and international practices related to resilience in transportation;
- A survey of highway agency staff working on resilience efforts within their agency; and
- Interviews with highway agency staff to document their resilience efforts.

Information gathered has been incorporated into the following structure within this report:

- Chapter 2 addresses resilience policies in transportation;
- Chapter 3 explores resilience definitions, metrics, and frameworks;
- Chapter 4 examines the resilience survey of state DOTs;
- Chapter 5 shares case examples; and
- Chapter 6 highlights conclusions, findings, and suggestions for future research.

CHAPTER 2

Evolution of Highway Resilience

Security and protection of assets is fundamental to ensure a safe and functional society. This chapter presents a review of the evolution of policies related to infrastructure and highway resilience. The review notes the shift in policy over the past several decades from risk reduction and protection of critical infrastructure assets from potential hazards, initially highly concentrated on direct threats, toward improving infrastructure resilience (the ability to absorb and quickly recover from events) from a wider range of hazards, including both direct and natural threats. Figure 1 has been included to highlight major policy initiatives related to system resilience and also major disasters in the United States over the past several years.

Modern examples of legislation and policies implemented to support security and protection needs of critical infrastructure include the 1963 establishment of the National Communications System, which was established to ensure that officials could efficiently communicate with the public in emergency situations. This was followed by the creation of the Federal Emergency Management Agency (FEMA) in 1979, whose mission was to form and maintain "a secure and resilient nation with the capabilities required across the whole community to prevent, protect against, mitigate, respond to, and recover from the threats and hazards that pose the greatest risk." After the World Trade Center bombing in 1993 and the September 11, 2001, terrorist attacks, a Presidential Commission on Critical Infrastructure Protection was established, and in 2002 the first *National Strategy for Homeland Security* was published. This publication was followed by the *National Strategy for the Physical Protection of Critical Infrastructures and Key Assets* and the Homeland Security President Directives 7 and 8 in 2003 (Hart and Ramsay, 2011). These publications helped to develop what is known today as the National Infrastructure Protection Plan (NIPP), which includes the following updated list of 16 critical infrastructure sectors that if incapacitated or destroyed could have a debilitating effect on security, national economic security, or national public health or safety:

- Chemical;
- Commercial facilities;
- Communications;
- Critical manufacturing;
- Dams;
- Defense industrial base;
- Emergency services;
- Energy;
- Financial services;
- Food and agriculture;
- Government facilities;
- Health care and public health;
- Informational technology;

Figure 1. Resilience timeline.

- Nuclear reactors, materials, and waste;
- Transportation, and
- Water and wastewater.

In response to climate and environmental concerns, the U.S. DOT established the Center for Climate Change and Environmental Forecasting in 1999, which is a focal point for information and technical expertise on transportation and climate change.

In 2006, the Critical Infrastructure Task Force of the Homeland Security Advisory Council argued that the government was too focused on protecting assets from terrorist attacks with little mention of protecting those same assets from a variety of threats, including climate change

and natural hazards. This led the House Committee on Homeland Security to hold a series of hearings in 2008 to address issues related to resilience. After this, policies became more focused on resilience (Moteff, 2012).

In 2005, FHWA's Office of Planning, Environment, and Realty led a U.S. DOT study that analyzed the vulnerability of the Gulf Coast states through two separate studies, phase 1 in 2008 and phase 2 in 2015. The focus of the studies was to better understand the vulnerabilities to transportation assets from climate change and to determine strategies for improving system resilience (FHWA, n.d., d). Several tools and reports were developed as part of this study including vulnerability assessment tools, criticality assessment reports, and adaptation frameworks.

In 2013, Presidential Policy Directive 21 (PPD-21) was issued, and the supporting report *NIPP 2013: Partnering for Critical Infrastructure Security and Resilience*, also referred to as the *National Plan*, was published to guide the national effort to manage risk to the Nation's critical infrastructure (Moteff, 2012). This directive updated the existing NIPP; established a vision, mission, and goals; and built on the previously published critical infrastructure risk management frameworks from 2006.

Many of these efforts and policies are based on protection from terrorist attacks; however, it has been recognized that many of the same principles apply when planning and protecting national infrastructure from other non-manmade hazards such as natural threats, including hurricanes, floods, earthquakes, landslides, wildfires, tornadoes, ice and snowstorms, debris flow, and geohazards. The basis for many of the policies relating to the identification and protection of critical infrastructure is drawn from risk analysis and management methods and procedures. The connection between direct and non-direct threat analysis lies in the ability to use probabilistic approaches to analyze threats, estimate consequences, and assess vulnerability of infrastructure to a range of threats deemed possible for any identified critical infrastructure asset.

The Moving Ahead for Progress in the 21st Century (MAP-21) (P.L. 112-141) signed into law by President Obama on July 6, 2012, continued to move the industry forward for the protection of highway assets by requiring states to establish a process for developing a risk-based, performance-based asset management plan to be reviewed and updated every 4 years for preserving and improving the condition of the National Highway System (NHS) (FHWA, 2012).

This act created a streamlined and performance-based surface transportation program and built on many of the existing highway, transit, bike, and pedestrian programs and policies established in 1991. If an agency fails to develop and implement a plan by the beginning of the second year after the Secretary's rulemaking was published and the process was established, there will be a reduction of 35% of the federal share for the National Highway Performance Program (NHPP) projects in that fiscal year. The developed plan needs to include the following at a minimum:

- A summary list of salient assets, including condition, of the state's NHS pavements and bridges;
- Asset management objectives and measures;
- Performance gap identification;
- Life cycle cost and risk management analysis;
- A financial plan; and
- Investment strategies.

Risk has been broadly defined within MAP-21, leaving it open to agencies to determine which risks will be addressed within their overall asset management plan. At a minimum, agencies are required to address risks that may affect pavements and bridges but are encouraged to include all assets within the agency's right of way. Agencies should also consider risk at the agency, program, and project levels (FHWA, 2012).

Recently, there has been an effort to focus on resilience with regard to terrorism as well as to natural hazards that may be caused by the effects of climate change. FHWA Order 5520, published in December 2014, provides a framework to enable agencies to better prepare for and be resilient to hazards due to climate change and extreme weather conditions. The purpose of this policy is to establish FHWA's policy on preparedness and resilience to climate change and extreme weather. The directive focuses on how "changing climate (such as higher temperatures, sea-level rise, and changes in seasonal precipitation and the intensity of rain events) and extreme weather events are affecting the lifecycle of transportation systems and are expected to intensify" (U.S. DOT, 2014).

In July 2015, the National Infrastructure Advisory Council (NIAC), which provides the President of the United States with advice on the security of the critical infrastructure sectors and their information systems, provided recommendations as to the nation's transportation sector resilience. The NIAC provided three key observations and three key recommendations to the president to address resilience of the transportation sector (NIAC, 2015):

Key observations:

- Systemic risks are not well understood by mode, jurisdiction, regions, or the interdependence between critical sectors. In addition, emerging risks from cyber threats, extreme weather, sea-level rise, aging infrastructure, and workforce changes are not well understood.
- While national resilience policies are well established, they have not been well integrated into practice.
- Chronic underinvestment in the nation's transportation infrastructure and the lack of monetization of the resilience have limited the integration of resilience into investments.

Key recommendations:

- Create a baseline of current risks and establish a federal vision for transportation resilience.
- Develop the analytic tools, models, and exercises to better understand and plan for emerging risks and interdependencies.
- Use the results of these efforts to operationalize resilience by increasing funding and implementing effective federal practices, procedures, and procurement processes.

The NIAC noted that there is an urgent need to rebuild the U.S. transportation infrastructure that has suffered neglect and increasing disruptions from natural and manmade threats. It was noted that in order to achieve a truly resilient transportation sector, a long-term, systematic approach needs to be incorporated into the sector through long-term investments. The following section outlines some of the ongoing activities at state DOTs to address improving system resilience in the face of climate change and extreme weather events.

Incorporation of Resilience Into Highway Programs

In reaction to evolving policies at the national level and recommendations for critical infrastructure, transportation agencies and organizations have responded through specific efforts aimed at transportation infrastructure. Along the lines of system resilience, AASHTO held a workshop in May of 2012 titled *Adapting Infrastructure to Extreme Weather Events: Best Practices and Key Challenges* and produced a background paper for a workshop that details what states are doing to mitigate potential natural threats to their respective transportation systems with respect to climate change. The purpose of the workshop was to provide a mechanism for states to exchange information on how they are addressing climate change and extreme weather events (Meyer, Choate, and Rowan, 2012). At the time of the publication, several key stressors were noted for transportation assets, including temperature extremes, precipitation extremes, sea-level rise, and increases in the number and intensity of hurricanes.

A few states provided information as to the expected performance of their facilities as a result of climate change and extreme weather that was included in the background paper. California noted that it was expected that the state would experience fewer extreme cold days and more extreme hot days, which will increase the risk of buckling highways as well as potential flooding of tunnels, coastal highways, runways, and railways. Michigan noted reviewing its snow and ice removal strategies to be better prepared for more major snowstorms. In addition, Michigan DOT is considering removing piers in new bridge designs to reduce the potential for bridge scour in the future. Washington State noted a need to assess upsizing drainage culverts to accommodate expected increases in demand flow from more intense rainfalls, glacial thawing, and sea-level rise (Meyer, Choate, and Rowan, 2012). The report also noted efforts by state agencies to include climate change and extreme weather events in their planning efforts, including those in Florida, California, Oregon, and Maryland. Maintenance activities were also documented to address extreme weather and climate change, including Maine and Oregon DOTs that are including culvert vulnerability assessments in an effort to identify areas of concern and to improve system resilience. The report concluded that agencies should move toward incorporating climate change and extreme weather planning to increase system resilience in their asset management plans and have begun to address reducing risk from these events through design, operations, and maintenance programs.

Also noted in the background document, at the direction of its governor, the State of California produced a document to address sea-level rise at the statewide level to incorporate sea-level rise projections into their planning and decision-making processes. This document is meant to provide projections that can be used for risk-based scenario planning and assessments, including long-range transportation plans (LRTPs) and vulnerability assessments. According to the document, "California Executive Order S-13-08 required all state agencies planning construction projects in areas vulnerable to future sea-level rise to 'consider a range of sea-level rise scenarios for the years 2050 and 2100 in order to assess project vulnerability and, to the extent feasible, reduce expected risks and increase resiliency to sea level rise'" (Georgetown Climate Center, 2013; Office of Governor Edmund G. Brown, Jr. Online). The Executive Order was established in 2009 and also required the California DOT (Caltrans) to conduct a vulnerability assessment of transportation systems and make recommendations for future investment to curtail losses of infrastructure and improve safety. The motivation to reduce risks associated with sea-level rise provides a good example of an agency or state analyzing threats that are likely and to develop mitigation strategies to protect against these threats, resulting in a more resilient transportation system.

Since the 2012 AASHTO workshop, other states have begun to initiate proactive efforts to address extreme events. As a result of extreme flooding in September 2013 and destructive rockfall events along key corridors in the state, Colorado DOT has launched a pilot project known as the I-70 Risk and Resilience Pilot, to assess hazards along the I-70 corridor from border to border to proactively identify areas with high probability of losses from a range of threats including natural (e.g., flooding) and direct (e.g., bridge strikes). The project has purposively engaged a wide range of Colorado DOT staff from all five regions of the agency as well as its headquarters staff and executives throughout the year-long study. By engaging a wide range of engineering, maintenance, operational, planning, and executive staff, the project is benefiting from the knowledge of each of these areas of expertise and working to ensure buy-in across the agency for the proactive approach to system resilience management. The I-70 Risk and Resilience Pilot provided Colorado DOT with the following three key pieces of information important to decision making:

- A criticality rating reflecting each asset's effects on overall system performance;
- An annualized monetary risk from potential threats for each analyzed asset; and
- The measure of resilience of each analyzed asset, reflecting the effect to the traveling public from potential threats.

Colorado DOT is beginning to explore potential uses of the information ranging from maintenance, operational planning, and project design. In addition, Colorado DOT will assess the usefulness of the information provided by the process and determine if future analyses should be conducted (Colorado Resiliency and Recovery Office, Online).

Several state DOTs participated in the FHWA Climate Change Resilience pilot studies, and some have framed their approaches to climate change in terms of system resilience. Washington DOT participated in phase 1 and 2 of the climate change pilots and developed information to help drive decision making based on system vulnerability assessment. The study resulted in 11 site-specific vulnerability assessments and adaptation strategies focused on improving system resilience from potential future flooding. The second phase of the assessment concentrated its efforts on the Skagit River Basin, which is the third largest river on the West Coast. The basin contains five dams and floods frequently in both urban and rural areas. For each of the 11 sites, several adaptation strategies were developed, ranging from operational preparation, alignment changes, culvert enhancement, and increasing water storage (FHWA, Online, d).

State DOTs are looking to the future to analyze and prepare for potential threats that may be brought on by unplanned events. Some agencies have begun to analyze their personnel roles and responsibilities and training needs to address resilience of highway systems.

In 2013, FHWA published a report on how agencies should address system resilience through their asset management plans (FHWA, 2013b). The document notes some of the lessons learned from Hurricanes Lee, Irene, and Sandy in the Northeast, and the following several recommendations were made to transportation agencies:

- Develop a risk assessment of the state's transportation infrastructure;
- Strengthen existing transportation networks;
- Protect transit systems and tunnels against severe flooding;
- Strategically expand transportation networks in order to create redundancies; and
- Build for a resilient future with enhanced guidelines, standards, policies, and procedures.

FHWA notes that a strong risk-based asset management plan will help agencies better understand their ability to withstand physical threats to their system by understanding system redundancy, robustness, and resilience.

In the summer of 2017, after the development of the draft version of this report, which was vetted by the project panel, FHWA published additional information and guidance on the incorporation of resilience in project development (FHWA, 2017). Given the publication occurred after the initial development of this report, a cursory review was made of the document only. The guidance includes information on the inclusion of climate change models within the project development process and provides information on how agencies can downscale climate models to incorporate such climate change information within their processes. FHWA notes the need for improved models to conduct economic analyses of the benefits of climate change adaptation measures and the need for information on how assets are anticipated to perform under various climate stressors.

Agency Personnel Roles, Responsibilities, Training, and Education

State DOTs are responsible for providing methodologies that can be used throughout the state to promote resilience practices that align with federal regulations. These policies can be used to ensure resilience throughout all components of the government, including laws that govern local

developmental decisions. Local governments play an important role in resiliency practices. Since local governments are directly responsible for community planning, they have a greater understanding of the potential risks that could affect their respective areas, which in turn strengthens mitigation practices to promote greater resilience.

One of the largest concerns with climate change is sea-level rise and the potential adverse effects it will have on transportation system resilience. Caltrans produced a guidance document to inform their staff on how to assess vulnerabilities associated with sea-level rise. Caltrans employees are instructed to use a two-part analysis to determine if sea-level rise mitigation is required in project programming or design (Georgetown Climate Center, 2011). The document also notes the uncertainties associated with climate change modeling, yet the agency is working toward incorporating these factors into their processes to improve their system resilience and reduce future risks.

Vermont has developed a three-tiered training program, Rivers and Roads, which was developed in cooperation with the Vermont Department of Environmental Conservation's Rivers Program, the Vermont Department of Fish and Wildlife Fisheries Division, and the Vermont Department of Transportation Local Roads Program. The program is aimed at considering the river in the design, construction, and maintenance of transportation infrastructure in Vermont and is delivered through online and in-person modules (Vermont Department of Environmental Conservation, 2016). The training builds on the lessons learned from Tropical Storm Irene, which dumped 11 inches of rain on portions of the state and caused an estimated $733 million in damage in Vermont alone (Pierre-Louis, 2016).

FHWA published guidance on the establishment of incident command centers aimed at familiarizing transportation professionals with the components of incident command centers. The guidance was based largely on the Department of Homeland Security's National Incident Management System and on the Model Procedures Guide for Highway Incidents developed by the National Fire Service Incident Management System Consortium (FHWA, 2006).

Agencies are also seeking mechanisms to fund resilience strategies on highway systems, as described in the next section.

Funding Mechanisms for Resilience

While it is a requirement for transportation agencies to promote resilience in their transportation systems, many agencies find it difficult to fund such programs. Because of this, it is important for agencies to develop a strong asset management plan that will lead to the development of long-term asset management plans. According to FHWA, "Comprehensive transportation asset management plans (TAMP) could show the expected and desired projections of asset performance for more than 10 years into the future. A pragmatic TAMP would address the amount of investment required for the rehabilitation, preservation and maintenance of assets during their useful life" (FHWA, 2015). When agencies produce asset management plans that analyze future risk, it becomes easier to justify the use of the expenses needed to build and maintain such assets.

Other potential sources of funding to incorporate resilience include the FHWA Emergency Relief Program after a qualifying disaster has occurred. In January 2017, FHWA published a fact sheet that outlines how resilience can be incorporated into recovery efforts on those facilities that fall within the FHWA emergency relief (ER) program. Examples are provided to outline how an agency can incorporate resilience that reflects current design standards or provide an economic justification to demonstrate the anticipated reduced cost to the ER program from future events with more resilient designs.

For those facilities that may be eligible for FEMA grants, the FEMA Hazard Mitigation Assistance Guidance provides information on grants available to communities addressing post-disaster recovery to support the planning and implementation of long-term hazard mitigation measures as well as a Pre-Disaster Mitigation Program to help proactively address potential hazards before an event. In addition, the same guidance document includes information on FEMA's Flood Mitigation Assistance Program (FEMA, 2015).

Some not-for-profit and non-profit organizations have sponsored resilience competitions in the recent past as a way to promote forward thinking and incorporation of resilient designs into infrastructure. One example is the National Disaster Resilience Competition sponsored by the Rockefeller Foundation in 2014. A national competition took place in two phases with applicants from a range of cities, counties, and states. Ultimately, eight states and five cities/counties were selected to receive a portion of $1 billion distributed through the U.S. Department of Housing and Development (The Rockefeller Foundation, Online).

Federal and Other Transportation Resilience Initiatives

Federal and other transportation agencies and organizations such as FHWA, AASHTO, TRB, FTA, and ASCE have been developing initiatives to incorporate the concept and importance of resilience into transportation systems at federal, state, and local levels for over 10 years.

FHWA has funded numerous pilot projects and published many reports and much guidance related to climate change, vulnerability, and resilience. There is a full section on their website dedicated to resilience, with information related to adaptation frameworks, case studies, pilot projects, policy and guidance, publications, tools, webinars and workshops, and peer exchanges (FHWA, d). The goal of FHWA resilience efforts is to "develop resources and guidance materials for operating agencies to better prepare for the effects of extreme weather on transportation management, operations and maintenance" (FHWA Online, e). FTA has also funded resilience projects, especially after Hurricane Sandy recovery, and has funded multiple pilot projects since 2011 to conduct climate change adaptation assessment (FTA, Online, e).

Similarly, AASHTO approved a reorganization of their committee structure in November 2016 to add new subcommittees, including the Transportation System Security and Resilience (TSSR), which is chaired by Michael Lewis of Colorado DOT (AASHTO, 2016a). This new committee has the purpose of coordinating national efforts and identifying best practices to fill research gaps in order to promote resilience in transportation systems. The RSTS new action plan, adopted in May 2017, specifies all the committee's new initiatives and goals for the next 2 years (AASHTO, 2017). In addition, in January 2017, AASHTO's Special Committee on Transportation Security and Emergency Management published *Understanding Transportation Resilience: A 2016–2018 Roadmap for Security, Emergency Management, and Infrastructure Protection in Transportation Resilience* with the purpose of providing a discussion tool for other resilience-oriented committees and existing and future resilience-funded programs and initiatives (AASHTO, 2016b).

TRB has also played a role in promoting resilience initiatives in the transportation sector. A publication from July 2017, *TRB Resilience: Key Products and Projects*, explains in detail all the resilience initiatives sponsored by TRB in the past (TRB, 2017). In addition, resilience was identified as the number one NCHRP emphasis area for fiscal year 2017 and has been a hot topic for recent TRB Annual Meetings (2016 and 2017) (AASHTO, 2016b).

ASCE has also promoted resilience and established the Infrastructure Resilience Division in 2014 to advance the concept in infrastructure with a focus on community resilience,

disaster assessment, emergency technologies, civil and infrastructure lifeline systems, multi-hazard characterization, risk and resilience measurements, and social and economic impacts. In particular, it created the Risk and Resilience Measurements Committee to address the use of risk in civil infrastructure and lifeline systems and to build risk-based resilience standards (ASCE, Online).

As outlined in this chapter, the concept of infrastructure resilience has evolved over the past two decades, and emphasis is shifting to understanding how capable infrastructure is to recover from or resist events before they occur. Several states have begun to adopt resilient practices into their planning, maintenance, and operational management programs. Some states have begun to address resilience in their training and education programs as well, and recent initiatives by several professional organizations reflect the desire to further incorporate resilience into traditional planning, design, operations, and maintenance programs.

With the increased focus on the need for a resilient transportation sector in policy and guidance, there is a need to establish a firm definition of resilience in the highway sector in order to align the understanding among transportation professionals as to what a resilient highway system is and how to measure resilience. The next chapter of this report provides some insight as to current thinking for these concepts in transportation and other relevant sectors.

CHAPTER 3

Resilience Definitions, Metrics, and Frameworks

This chapter provides a range of resilience definitions from sectors outside as well as within transportation and analyzes the similarities and differences of these definitions. Next, a review of the variety of metrics being applied to assess resilience is discussed. Finally, several frameworks that provide processes for agencies to perform assessments of resilience are examined. This information is provided as a means to begin to understand the relatively immature state of resilience computational methods within the transportation sector.

The Department of Homeland Security (DHS) conducted the analysis of the range of definitions of resilience for infrastructure (U.S. DHS, 2011). Within the DHS study, the authors identified several key discriminators (goal of definition, event cycle addressed in definition, and approach to measuring resilience) to analyze and categorize resilience definitions for critical infrastructure, as shown in Table 1.

These discriminators have been broadly applied for resilience definitions to help identify similarities and differences between the resilience definitions included in this literature review. A review of definitions of resilience from both the highway sector as well as other related industries is provided here.

Resilience Definitions from Other Sectors

Resilience has many definitions, such as "the ability of a system to resist, absorb, recover from, or successfully adapt to a change in environment or conditions" (Moteff, 2012). Other definitions include factors related to a facility being able to continue operating at a diminished level, or where system performance fails gracefully or gradually instead of all at once, again capturing the "bend but not break" concept of resilience.

The National Research Council (NRC) defined resilience as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (NRC, 2012). NIAC published a report in 2009 that defined infrastructure resilience as "the ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event" (National Infrastructure Advisory Council, 2009). Furthermore, the United Nations (UN) defines resilience as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and effective manner, including through the preservation and restoration of its essential basic structures and functions" (United Nations, 2009). The National Academies describes the need for local communities to work with both the private sector and all levels of government to ensure there is "the ability to prepare and plan for, absorb, recover from and more successfully adapt to adverse events" [The National Academy of Sciences (NAS), 2012].

Table 1. Key discriminators used to develop consolidated resilience definitions (U.S. DHS, 2011).

	Discrete Options				
Key Discriminators	Goal	Maintain Continuity of Function	Graceful Degradation	Recovery of Function to Desired Function in Designated Time	Inhibit Basic State of Change
	Event Cycle	Before Event	During Event	Post Event	
	Approach	Outcome Based		Process Based	

Resilience is defined by ASME as "the ability to function through an attack or natural event or the speed by which an asset can return to virtually full function" (ASME Innovative Technologies Institute, 2009). Within the American Water Works Association (AWWA), resilience is defined as "the ability of an asset or system to withstand an attack or natural hazard without interruption of performing the asset or system's function or, if the function is interrupted, to restore the function rapidly" (AWWA Staff, ASCE/AWWA Committee, 2009). AWWA also identifies methods to improve system resilience by finding options that reduce at least one of the three elements that they use to define resilience: service denial, vulnerability, and likelihood.

When comparing the various definitions of resilience, one observation that can be made is the focus of the AASHTO Standing Committee on Research (SCOR), ASME, and AWWA definitions on the *post-event* portion and *event cycle,* unlike those definitions developed by NRC, NIAC, and UN, which have a broader focus on all three event cycles (before, during, and after an event). The NIAC definition also appears to address the proactive nature of resilience by calling out the need to "reduce the magnitude and/or duration of disruptive events" as well as "rapidly recover." In addition, the NIAC definition appears to capture the graceful degradation of assets through its note of resilient systems being those that can "anticipate, absorb, adapt to" events. Other research entities and researchers have also developed definitions of resilience as described next.

The Multidisciplinary Center for Earthquake Engineering Research sponsored by the National Science Foundation developed a framework (R4 Framework) that examines four main attributes of resilience:

- Robustness—the ability of systems, system elements, and other units of analysis to withstand disaster forces without significant degradation or loss of performance;
- Redundancy—the extent to which systems, system elements, or other units are substitutable, that is, capable of satisfying functional requirements, if significant degradation or loss of functionality occurs;
- Resourcefulness—the ability to diagnose and prioritize problems and to initiate solutions by identifying and mobilizing material, monetary, informational, technological, and human resources; and
- Rapidity—the capacity to restore functionality in a timely way, containing losses and avoiding disruptions.

These attributes are described in terms of resilience as "the ability of the system to withstand a disaster without significant degradation or loss of performance, the extent to which the system is capable to maintain functional requirements if significant degradation or loss of function occurs, the ability to diagnose and prioritize problems and to initiate solutions by identifying and mobilizing material, monetary, informational, technological, and human resources and the capacity to restore functionality in a timely way, containing losses and avoiding disruptions" (Tierney and Bruneau, 2017). This definition also addresses a broader range of the timeline associated with

events (before, during, post) and addresses more of the goal areas as outlined in Table 1, including maintaining functionality, recovery of functionality, and inhibiting change of state. Resilience definitions have also been developed by researchers for the freight industry.

When defining resilience for freight transportation systems, Ta et al. (2009) describe it as "The ability for the system to absorb effects from a disruption and continue moving traffic in an uninhibited manner . . ." and also say that this definition involves the flexibility, elasticity, and ability to recover from a disturbance. In this definition, resilience is defined by the measurement of reliability, travel time, travel speed, and vehicle count, which are used to measure overall system performance. The resilience of the freight system depends on the ability of the system to recover from/reduce the effects of disruptions in order to maintain freight mobility.

Resilience Definitions from Transportation

Resilience is a term that is relatively new in the transportation sector, therefore, it still has a range of definitions in literature. AASHTO's SCOR has defined resilience as "the ability of the transportation system to recover and regain functionality after a major disruption or disaster" (U.S. DOT, 2014b). In 2009, the AASHTO–TRB Transportation and Security Summit proposed that resilience in the transportation sector should be defined as "The ability of a system to provide and maintain an acceptable level of service or functionality in the face of major shocks or disruptions to normal operations" (AASHTO, 2016b). Another definition from FHWA Order 5520 explains resilience as "the ability to anticipate, prepare for and adapt to changing conditions and withstand, respond to and recover rapidly from disruptions" (U.S. DOT, 2014b).

While the AASHTO-TRB definition focuses primarily on the ability to function during and post event, the FHWA definition also includes the period before the event by stressing the need to "anticipate, prepare for, . . . changing conditions" as well as "recover rapidly from disruptions" (U.S. DOT, 2014b).

Other researchers within the transportation sector have identified various components or properties of resilience, for example, Murray-Tuite (2006) developed a resilience approach that describes the following 10 properties of a resilient transportation system:

1. Redundancy,
2. Diversity,
3. Efficiency,
4. Autonomous components,
5. Strength,
6. Adaptability,
7. Collaboration,
8. Mobility,
9. Safety, and
10. The ability to recover quickly.

Murray-Tuite (2006) went on to state that because resilience is tied to these 10 components, it is difficult to obtain a comprehensive measure due to the complexities and interactions between the components. This researcher also defined resilience as "a characteristic that enables the system to compensate for losses and allows the system to function even when infrastructure is damaged or destroyed." This definition appears to be most focused on the performance of a system during an event and also on graceful degradation of a system to continue to function despite an event occurring.

According to Heaslip et al. (2012), transportation resilience can be defined in ways that include the following:

- A system's ability to maintain its demonstrated level of service or return to that level of service in a specified time frame;
- A system's ability to compensate for losses to allow functionality, even when that system is damaged or destroyed;
- A system's ability to cope with unexpected conditions without complete failure; and
- A system's ability to absorb consequences of disruptions to reduce effects and maintain freight mobility.

This definition again is broader in terms of the event cycle and is focused on returning to functionality despite damage and without complete failure referencing the desire for graceful degradation. The ability to cope or absorb unexpected events or disruptions is also called out in the definition that reflects the broader range of goals as described in Table 1.

Internationally, the New Zealand Transport Agency has taken steps to measure resilience of the transport infrastructure and has also developed a definition of resilience that is more established than most with regard to asset management, though qualitative in nature. Their publication states that "the concept of resilience is wider than natural disasters and covers the capacity of public, private and civic sectors to withstand disruption, absorb disturbance, act effectively in a crisis, adapt to changing conditions, including climate change, and grow over time" (Hughes and Healy, 2014). This definition appears to reflect all three event cycles and goal areas related to maintaining continuity of functionality, and inhibiting state of change by absorbing disturbances. It also begins to address graceful degradation through the note to adapt to changing conditions but puts less emphasis on recovery time.

As part of this synthesis, a survey of state DOTs was conducted and is fully discussed in chapter 4. Of note, however, is the response provided by eight state DOTs that provided a definition of resilience as shown in Table 2.

A review of the definitions provided in Table 2 from state DOTs reveals that most fall short of capturing the before, during, and post time periods of emergency events, with most being focused on the post-event time period. Also missing in most is the graceful degradation of transportation assets to reduce or eliminate catastrophic failures.

All of the definitions provided for resilience within the transportation sector describe a system's ability to recover from a disaster, whether natural or attack based, with minimal loss of that system's functionality. As noted in the introduction of this synthesis, there are competing definitions of resilience that can be categorized in multiple ways. The work by DHS to develop a consolidated definition of resilience may be of use as noted in the introduction to this chapter. In general, the key components for a definition of resilience for highways appear to capture preparing for, absorbing, and recovering quickly from an event that disrupts service. Following the DHS key discriminators of definitions of resilience, most definitions appear to miss the mark on graceful degradation and inhibiting a basic state of change, meaning a system that does not fail or is damaged during an event. The key discriminators recognized by DHS for critical infrastructure include the full range of time periods in which resilience needs to be addressed by asset managers and owners. The key discriminators also reflect four goal areas to address that are not only focused on quick recovery but also address the need to restrict the state of change of some critical assets (hardening these assets to withstand events). Furthermore, recognizing that funds are limited, it is recommended that assets be built to "gracefully degrade" to avoid catastrophic failures that may increase injuries and loss of life. Finally, maintaining continuity of function through pre-event planning is addressed through these key discriminators. This type of analysis may be of use to state DOTs as they move forward with their resilience

Table 2. State DOT definitions of resilience.

State Agency	Resilience Definition
Minnesota Department of Transportation	Reducing vulnerability and ensuring redundancy and reliability to meet essential travel needs.
Oregon Department of Transportation	Uses a definition from the Oregon DOT (ODOT) seismic report: "To achieve rapid recovery, require government continuity, resilient physical infrastructure, and business continuity."
Arizona Department of Transportation	ADOT developed the Resilience Program to support its mission to provide a safe, efficient, cost-effective transportation system that can be compromised from the effects of heat extremes, dust storms, wildfires, flooding, landslides, rockfall incidents, and slope failures, and cope with the ever-growing cost of these threats.
Delaware Department of Transportation	Uses the concept in the Delaware Executive Order 41, which outlines resiliency practices to help mitigate climate impacts and reduce emissions.
Colorado Department of Transportation	Uses a definition provided by the Governor's Resiliency Framework: "The ability of communities to rebound, positively adapt to or thrive amidst changing conditions or challenges – including disasters and climate change – and maintain quality of life, healthy growth, durable systems, and conservation of resources for present and future generations."
New York State Department of Transportation	Uses the recommended guidance provided by the NYS 2100 Commission, which outlines how the state plans to identify areas where further resilience practices are needed.
New Hampshire Department of Transportation	Uses the NAS definition by default, which states "resilience is the ability to plan, absorb, recover and adapt."
Illinois Department of Transportation	Plan and invest in the state's transportation system to ensure that infrastructure is prepared for extreme weather events.

programs as a way to help identify resilient practices and policies that address a broader range of activities that can be implemented to provide more than quick recovery post event to transportation assets.

An outstanding issue as related to resilience analysis in highways is defining the relationship between resilience and risk. In order to understand this relationship, a short summary of risk definitions is provided next.

Risk Definitions

In order to understand resilience of the highway system, one must have a solid understanding of what risk assessment and management are and their relationship to resilience. Risk entails four elements: hazards, exposure, vulnerability, and consequence. A comprehensive definition of risk states that risk can be defined as "the potential for adverse effects from the occurrence of a particular hazardous event, which is derived from the combination of physical hazards, the exposure, and vulnerabilities" (The National Academy of Sciences, 2012).

FEMA's definition of risk focuses on the likelihood that a threat will harm an asset with some severity of consequences (FEMA, 2014). NIPP defines risk as the "potential for an unwanted

outcome resulting from an event or occurrence, as determined by its likelihood and the associated consequence" (U.S. DHS, 2009). The Office of Management and Budget defines risk as "a hazard, a probability, a consequence, or a combination of probability and severity of consequences."

According to AWWA, risk is defined as "a function of consequences, hazard frequency, or likelihood and vulnerability, which with point estimates is the product of the terms. It is the expected value of the consequences of an initiating event weighted by the likelihood of the event's occurrence and the likelihood that the event will result in the consequences, given that it occurs. Risk is based on identified events or event scenarios" (AWWA Staff, ASCE/AWWA Committee, 2009). Risk is estimated by the consequences that are expected to happen if a particular event occurs as well as the likelihood of the event occurrence.

A 2010 publication by the NRC reviewed the DHS's approach to risk analysis and noted that DHS relies heavily on quantitative models for risk assessment, which the committee felt this approach may underemphasize unquantifiable characteristics of risk. The committee recommended that both quantitative and non-quantitative attributes of risk be considered in the decision-making process (National Research Council, 2010b).

National and international organizations have also developed definitions for risk. The International Organization for Standardization's (ISO) ISO 31000 standard defines risk as "the effects of uncertainty on objectives" (ISO, 2009). Similarly, ASME developed a seven-step approach for Risk and Resilience Analysis and Management for Critical Asset Protection (RAMCAP Plus℠) in which risk is defined as "the potential for loss or harm due to an untoward event and its adverse consequences" (ASME, 2009).

The New Zealand Transport Agency developed a risk assessment tool based on AS/NZS 31000 which is equivalent to the ISO 31000 standard. Within this framework, risk is defined as "the chance of something happening that will have an impact on objectives. It is measured in terms of a combination of the likelihood of an event and its consequence" (New Zealand Transport Agency, 2014).

Within the context of highway asset management, FHWA has published a series of reports about risk-based transportation asset management (FHWA, 2013b). Within these reports, FHWA compares definitions of risk from different sources at the national and international levels. FHWA emphasizes that risk can be considered not only as threats or dangers but also as possible opportunities. FHWA formally defines risk as "the positive or negative effects of uncertainty or variability upon agency objectives" (FHWA, 2013b). Similarly, the Transportation Research Board (TRB) report *Guidebook on Risk Analysis Tools and Management Practices to Control Transportation Project Costs* defines risk as "an uncertain event or condition that, if it occurs, has a negative or positive effect on a project's objectives" (Molenaar et al., 2010).

The primary factors captured in this range of definitions are the acknowledgement and management of potential hazards and the probability of occurrence of applicable hazards that may result in losses dependent on present vulnerabilities. Next, understanding the relationship between risk and resilience is important to fully understand what is required to develop and manage a resilient highway transportation system.

Relationship Between Risk and Resilience

Evolving policy has led to some confusion as to the relationship and responsibility of infrastructure managers to reduce risk reduction and increase system resilience. The Congressional Research Service documented evolving policy that has moved away from protection and more toward resilience post 9/11 (Moteff, 2012). As noted, "improving resiliency reduces risk primarily by reducing vulnerability to and potential consequences of an attack or natural event."

This evolution of the relationship between risk and resilience has been seen through various federal reports and directives since 2006. As noted in the 2010 *National Security Strategy*, encouraging incentives to design structures and systems that can withstand threats, incorporating redundancy and decentralizing critical operations to reduce vulnerability, developing and practicing emergency response plans, and investing in infrastructure to maintain condition and performance are critical to improve resilience and reduce potential losses from applicable threats. Subsequently, Presidential Decision Directive (PPD-8), *National Preparedness*, issued by the Obama Administration, sought to improve "the security and resilience of the United States through systematic preparation for threats that pose the greatest risk . . . (U.S. Department of Homeland Security, Online, c)."

Efforts have been made to conceptualize the quantitative relationships between risk and resilience in a graphic that depicts the degradation of performance after the event occurs, the bottom out time, and the time required to recover to initial performance. The metrics in the conceptual quantitative model included time and percent performance, referring to the level of performance the asset or system is able to perform at after an event occurs and before full performance is achieved. Figure 2 illustrates a quantitative model.

As noted previously, as risk or the expected financial loss decreases, resilience increases. By reducing vulnerability to a threat (moving toward a value of 0), resilience is highest and the expected risk tends toward zero. By understanding the susceptibility of an asset to loss or failure and taking steps to reduce that vulnerability, owners can move toward a more resilient, less risk-adverse state. As anticipated financial losses or risk increase, system resilience decreases. Also, as an asset or system becomes more vulnerable to threats, the risk increases and resilience decreases. Figure 3 provides an example of the conceptual relationship between risk, resilience, and vulnerability.

It is important to understand the relationship between risk and resilience to allow the reader to reflect on the materials presented in this synthesis as related to highway resilience within the context of more well-established risk management and assessment methods.

Identifying risks is an important step in determining the resilience of a transportation system. By using risk analysis and performance-based measurement approaches, transportation agencies are able to identify weaknesses within their respective systems to determine the potential system level of resilience. According to Herning et al. (2016), "Risk analysis and performance-based approaches can be used to quantify reliability of infrastructure, inform prioritization of interventions, assess life-cycle outcomes related to infrastructure management decisions, and achieve performance objectives. . . ." When transportation agencies analyze risk to inform resilience, they are better able to identify areas that need the most improvement to become more resilient.

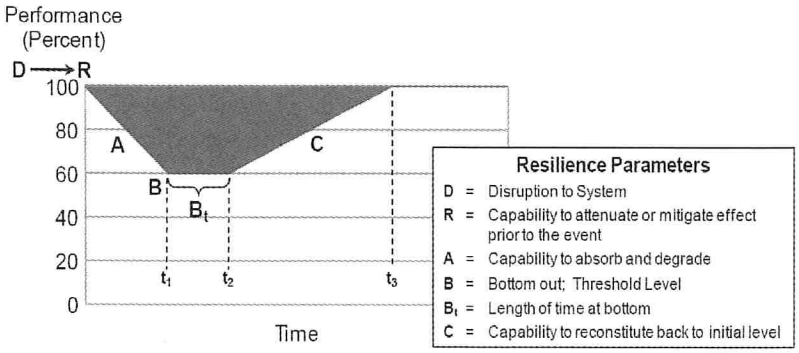

Figure 2. Resilience profile (U.S. Department of Homeland Security, 2011).

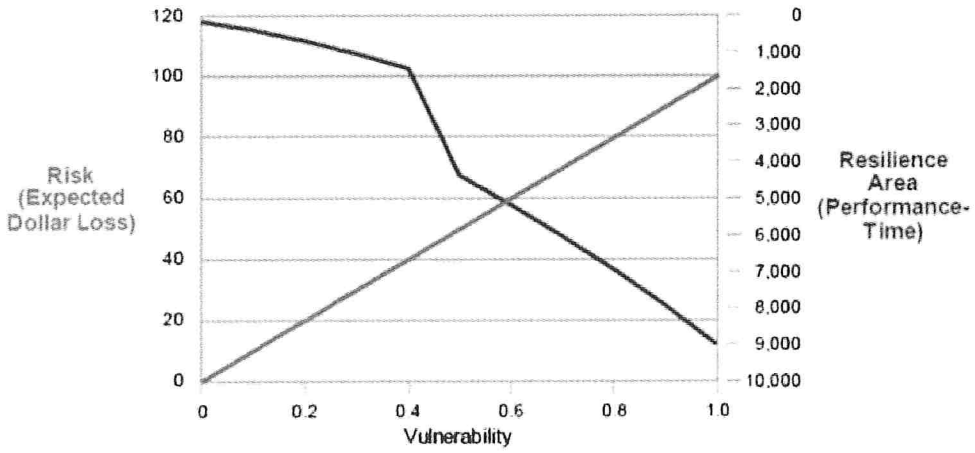

Figure 3. Relationship between risk, resilience, and vulnerability (U.S. Department of Homeland Security, 2011).

However, as noted by Jackson (2008), addressing inherent risks can result in the layering of measures for each identified, relevant threat, which often is not sustainable, whereas focusing on resilience and reducing the consequences should a threat come to fruition, may offer more methods to reduce risk. In addition, as noted by the Congressional Research Service, "Reducing risks by building higher fences and deploying more guards around a particular facility or asset (protection) is very different than reducing risks by building a second facility or asset somewhere else or strategically stockpiling replacement equipment that can get the facility or asset up and running again quickly (resilience)." In some cases, it may also be impossible to protect from all applicable threats, and thus incorporation of resilient practices into a system may be the only plausible solution.

After reviewing the range of resilience definitions and the relationship between risk and resilience, the next section of this chapter focuses on how to measure resilience and those studies that have been published reflecting a range of approaches to measuring resilience.

Resilience Metrics and Indices

The concept of resilience is still being formalized within many sectors, and in many cases is dependent on the preference of measurement of resilience (e.g., time, number of vehicles). Currently, there is no standard measurement for resilience within highway analysis, which is echoed in the state DOT survey results in the survey conducted for this research, in which 92% of the states responding noted that they do not currently have specific metrics for resilience in place. The method by which resilience is measured often depends on what is most important to policy makers. For example, "if monetary losses are important, it may be more appropriate to measure the total (or net) loss of revenue associated with the disruption" (Moteff, 2012). On the other hand, if policy makers are more concerned about the public need to use the damaged facility or asset, it may be appropriate to measure resilience in terms of how quickly the damaged asset or facility was able to resume normal operations. The following review has been categorized into empirical field measurements of resilience metrics and measurements of resilience gathered through modeling efforts. Very few studies were identified that measured resilience during an event and were able to compare the performance before and during an event. Most studies appear to be seeking to use existing data sources to reflect resilience through operational measures such as travel time. One study noted that when agencies are defining resilience metrics, it is important that the metrics chosen are broad enough to be used to measure resilience across the

board. Hughes and Healy (2014) note that studies tend to fall into one of two groups: qualitative frameworks that reflect resilience and quantitative studies that seek to measure metrics of resilience through more elaborate modeling approaches.

In order for an agency to measure resilience, it must be understood what components compose resilience. Parkany and Ogunye (2016) used previous work to identify multiple potential metrics for each of the four components of resilience (robustness, redundancy, resourcefulness, and rapidity), including hours of congestion, travel time index, pavement condition, distance to alternative routes, and availability of safety (courtesy) service patrols (Tierney and Bruneau, 2017). Next, information was gathered from readily available data sources, and the metrics were applied to 10 corridors in the Commonwealth of Virginia. The authors concluded that continuous data were difficult to work with, however, they found some additional value in the metrics when these data were converted to categorical data, but they noted that additional work is needed to finalize the metrics and data sources. Of note is the use of existing performance metrics cast in the light of resilience without the need to create additional metrics from scratch, which should reduce barriers to measuring resilience (Murray-Tuite, 2006).

The Multidisciplinary Center for Earthquake Engineering Research also recognized the four Rs of resilience but expanded the metric categories to include four components of resilience: technical, organizational, social, and economic (TOSE) to develop the TOSE method. These components are used to develop resilience metrics that can be used by any sector to mitigate the effects caused by natural hazards (Tierney and Bruneau, 2017).

Transportation agencies have a need to analyze threats that cause failures in their systems, but they also need a way to be able to measure their systems' resilience to those threats. Resilience metrics provide a way for an agency to take what they have learned from their risk analyses to measure the resilience of their transportation system. Tierney and Bruneau (2017) state that "The R4 approach highlights the multiple paths to resilience. Investments can improve all four resilience components—robustness, redundancy, resourcefulness, and rapidity. The TOSE framework emphasizes a holistic approach to community and social resilience, looking beyond physical and organizational systems to the effect of disruptions on the social and economic systems." By using both of these frameworks, transportation agencies will be able to create resilience policies that not only will take into account the functionality of the asset but also will look at the social and economic implications that come along with natural and manmade threats.

The Mountain-Plains Consortium developed a framework and metric index to evaluate the resiliency of the light rail system in the Denver Metro area (Marshall, 2015). The Transportation Economic Resilience (TER) rating system was developed and reflects the effect of spikes in fuel prices on individuals' income across the region for home-to-work trips. Using 2,832 transportation analysis zones (TAZ), the authors assigned a TER score to each TAZ and were able to assess how resilient each zone is to sudden spikes in fuel costs that reflected the ability to mode shift, the increased costs associated with each mode, and the distance and time associated with travel between home and work in each TAZ. Not surprisingly, three primary contributors to the TER scores include household proximity to downtown, median household income, and availability of multimodal transportation options.

A similar study was conducted for Mississippi DOT after Hurricane Katrina that sought to develop metrics to reflect the resilience of regions post event (Zhang et al., 2010). Several resilience indicators, including travel time, average trip length, percentage of freight vehicles traveling under the 85th percentile speed, percentage of total length of highway open to freight traffic in the network, and proportion of freight traffic that is able to maintain schedule were considered in the study. The authors used a measure of resilience (MOR) to capture the reduction in any

of the resilience indicators before and after an event. The MOR can be calculated for each of the resilience indicators using the following equation:

$$\text{MOR} = \frac{(RI_{Before} - RI_{After})(1 + t^{\alpha})}{RI_{Before}}\%$$

where

RI_{Before} = resilience indicator before an event;
RI_{After} = resilience indicator after an event;
t = total time required to restore the capacity (year); and
α = system parameter related to network size, socioeconomic status, government policy, etc.; used $\alpha = 0.5$ in case study.

Ip and Wang (2011) proposed a measure of resilience that reflects the weighted average number of reliable passageways with all other nodes in a network. The method presented takes into account the population of the various nodes being serviced by the rail system analyzed. The authors introduced a concept known as "friability," which represents the reduction in network resilience caused by a disruption to the network such as a disaster or an attack. The authors applied their approach to the Chinese rail network and assessed the reliability of the network.

Jenelius et al. (2006) introduced a metric that reflects the change in travel costs before and after an event that may limit travel on particular links. Using a sparse network in the northern part of Sweden, the authors used traditional models, such as user equilibrium, to assign traffic to the network based on the assumption that travelers will choose the least costly travel route between their origin and destination. They also assumed that travel time is independent of the traffic demand on each link and justified their assumption by noting the very low traffic demands in the northern Sweden area studied. The authors tested their approach by randomly closing a link on the network, and then closing the most important link on the network, which is identified as the link that results in the highest increase in travel time when removed from the network. The authors also captured unmet demand, those trips that could not be completed, through their analysis. Finally, by using visualization in geographic information systems (GIS), the authors differentiated between the importance of each link that serves origin–destination pairs in northern Sweden based on each link's effect on increased travel costs and the unmet demand that remained when each link was removed from the network.

A similar metric was developed by Chen and Miller-Hooks (2012), who studied the ability of intermodal freight networks to withstand and recover from disruptions. Their metric takes into account predisaster planning and recovery post disaster and reflects the demand that can be serviced before and after a disaster.

Adams et al. (2012) also studied freight resilience metrics by studying truck speeds and counts along the I-90/94 corridor in Wisconsin during two weather events in 2008. The authors focused their efforts on measuring two periods referred to as reduction and recovery; they represented the time passage between the start of the event and when the system reaches its lowest performance level, and the time passage between the lowest performance level and the time to recovery (pre-event conditions). By sampling Global Positioning System–equipped trucks on the corridor during two major weather events (a blizzard and a flooding event), the authors were able to develop two metrics, referred to as alpha and beta, which represent the angle of deterioration and recovery triangles to represent freight resilience on the I-90/94 corridor during significant weather events.

Resilience metrics for transit systems have also been developed by researchers at the Mineta National Transit Research Consortium (Nassif et al., 2017). The study addressed transit system

resilience by focusing in on three key areas: transit bridge infrastructure resiliency, public transit system resiliency, and efficiency of transit systems with a focus on disability paratransit service. The study used structural health monitoring, finite element analysis, and remote sensing to establish resilience metrics for transit bridge infrastructure. Vulnerability, resilience, and efficiency in recovering from a major natural disaster were studied for the public transit system as a whole by adapting readily available metrics to transit. Specific metrics included change in travel time, recovery time, change in travel speed, and number of reliable routes. And travel time and trip delay were noted as the more significant metrics for modeling the efficiency of transit systems.

Indices

Some research has been conducted on the development of indices to measure resilience. Foster (Online) developed a Resilience Capacity Index that captures an area's ability to respond to future stressors into a single metric that includes 12 indicators, including economic, socio-demographic, and community connectivity. The researchers went on to apply the index to the United States as a whole and rated various metro areas on a scale from very low to very high by categorizing scores. The University of South Carolina has developed a similar index: the Social Vulnerability Index for the United States (SoVI). This index captures 29 socioeconomic variables at the county level that are believed to reflect a county's ability to prepare for, respond to, and recover from hazardous events ranging from natural disasters or disease outbreaks (University of South Carolina, Online). Figure 4 includes a recent version of the SoVI metric for the United States.

Of note from the review of the resilience metrics and indices is the lack of consensus on resilience metrics. Many studies have pulled metrics from operational areas (such as reliability) and related metrics (such as travel time, delay, and travel speed) to reflect the resilience of transportation systems; most of these metrics relate to the speed at which the system is brought back into full service or the amount of time operating at partial service capacities. Metrics appear to be lacking for the bulk of the Rs of resilience, including robustness, redundancy, resourcefulness, and rapidity, and exclusively relate to the ability of the agency to rebound. The last section of this chapter focuses on methods by which agencies can begin to develop a repeatable process to assess resilience of their systems often referred to as frameworks.

Frameworks for Resilience

Some of the challenges faced by transportation agencies when beginning to address system or asset resilience is how to integrate resilient solutions into their existing programs, including asset management, operations, design, and maintenance. The broad range of publications from federal agencies that tackle the topic of resilience reflects the potential confusion and lack of full integration of resilient practices among transportation agencies. For example, FHWA has published multiple guidance documents on the topic of resilience, ranging from risk-based asset management, climate change and extreme weather guidance, the FHWA Emergency Relief Program Manual, and planning and design guidance (FHWA, 2013a, 2013b, and 2016). In this section, models for structuring the assessment of resilience are described along with documented efforts by transportation agencies to begin the assessment of system resilience.

In order to understand resilience, it is important to know the different range of dimensions, principles, and measures of resilience. To develop an implementable approach for resilience measurement and improvement, it is important to define its dimensions. Different approaches have been developed incorporating dimensions of resilience at different levels such as individual, community, design, economic, and strategic planning.

Social Vulnerability to Environmental Hazards
SoVI 2010-2014
High (Top 20%)
Medium
Low (Bottom 20%)
Social Vulnerability Index 2010-2014
Data from the American Community Survey 2010-2014, 5 Year Census Data Product - ACS 2010-2014
HVRI

Figure 4. Social Vulnerability Index for the United States (University of South Carolina, Online).

NIAC differentiates between approaches related to people and processes, and the structure of infrastructure and assets (National Infrastructure Advisory Council, 2010). Other studies have identified different principles for resilience such as robustness, redundancy, resourcefulness, rapidity, and adaptability (Bruneau et al., 2003). Figure 5 summarizes some potential attributes of resilience.

The incorporation of resilience management into an agency's decision-making process requires a broad approach that considers long-term infrastructure resilience and economic optimization rather than the short-term return on investment perspective. In addition, risk and resilience management approaches should be considered complementary and are not mutually exclusive (New Zealand Transport Agency, 2014). Without the inclusion of resilience management, an owner may inadvertently invest in risk reduction across the system without addressing the needs of the system in terms of service delivery. A resilience management plan allows for the identification of critical infrastructure corridors or networks that provide for the required service levels of the overall system. One requirement of any resilience management plan is the prioritization of assets in terms of their ability to withstand specific

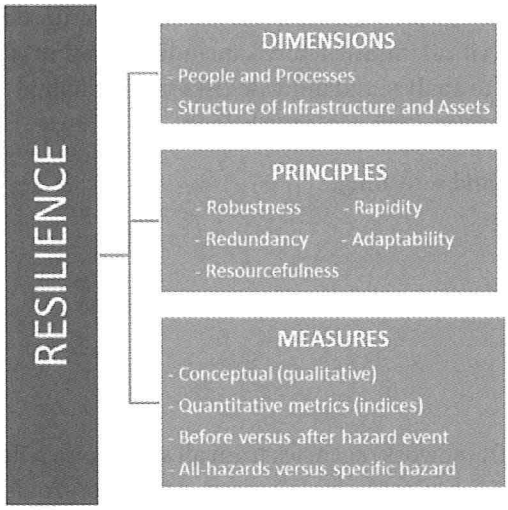

Figure 5. Resilience attributes (New Zealand Transport Agency, 2014).

threats. For example, to ensure continuity of service, agencies must study their system as a whole and identify high priority origin–destination pairs to ensure service on critical segments of the system to allow for flow of essential traffic, freight movement, and defense movement, if applicable. The level of resilience could be further refined by segment or corridor with design standards that reflect a required passage of flood events, debris flow, or embankment scour. The identified level of resilience could then be incorporated into a risk and resilience asset management plan.

DHS developed the National Mitigation Framework as a reference for agencies to learn to lessen the effects that are brought on by threats in hazards through mitigation strategies in order to promote resilience for their systems. The framework states that "Demonstrating clear and measurable returns on investment through mitigation is essential to that dialogue and necessary to build a resilient, risk-conscious culture" (U.S. Department of Homeland Security, 2016). The authors also note that becoming a resilient society is dependent on managing the entire spectrum of possible risks, which includes natural threats as well as manmade threats.

The New Zealand Transport Agency developed and implemented a framework to measure resilience of transport infrastructure (road and rail) based on the New Zealand Treasury's National Infrastructure Plan. The framework can be applicable at various scales, including asset, network/route, and regional and produces a range of resilience scores reflecting the following for each agency:

- A robustness score,
- A redundancy score,
- A safe to fail score,
- A change readiness score,
- A networks score, and
- A leadership and culture score.

The framework provides an approach to combine these scores to produce an overall agency resilience score ranging from 1 (low resilience) to 4 (very high resilience) (New Zealand Transport Agency, 2014).

ASME (2009) published a framework for the assessment of critical infrastructure, RAMCAP, which is applicable to 16 critical infrastructures, including transportation. The framework provides a seven-step process to analyze and mitigate risks from potential terrorist attacks on critical infrastructure assets. The seven steps are listed below:

1. Asset characterization and screening,
2. Threat characterization,
3. Consequence analysis,
4. Vulnerability analysis,
5. Threat assessment,
6. Risk assessment, and
7. Risk management.

Using this seven-step framework, agencies from all sectors are able to identify, analyze, and potentially mitigate risks associated with terrorist attacks to provide a much more resilient system.

AWWA has taken the RAMCAP approach to assess resilience in the water/waste water sector and developed an industry standard referred to as the AWWA J-100-10 (AWWA Staff, ASCE/AWWA Committee, 2009). The approach has been used to meet three major objectives in the water sector:

- To define a common framework that can be used by the water sector to assess human-caused and natural hazards risk to their systems;
- To develop risk-based vulnerability analyses and value-based prioritized actions to reduce risk and enhance resilience; and
- To provide an efficient and consistent mechanism that can be applied to both private and governmental (federal, state, and local) sectors to report essential risk and benefit information to operators of utilities, local and state governments, DHS, U.S. EPA, and others with a need to know (AWWA Staff, ASCE/AWWA Committee, 2009).

When used for the water sector, RAMCAP has provided a "consistent, efficient, and technically sound methodology to identify, analyze, quantify, and communicate the level of risk and resilience" (AWWA Staff, ASCE/AWWA Committee, 2009).

FHWA (2012) produced a framework to assess vulnerabilities due to climate change and extreme weather. The framework is made up of three steps: defining study objectives and scope, assessing vulnerability, and incorporating results into decision making. By employing these three steps, transportation agencies are better able to prepare for and recover from extreme weather events and effects of climate change; this will lead to a more resilient system. Figure 6 details the process.

Summary

This chapter provided an overview of resilience metrics, indices, and frameworks for assessment. It should be noted that resilience metrics within the transportation sector appear to be lacking and are often drawn from existing operational measures related to system reliability, which fails to provide methods to address all four components of resilience: robustness, redundancy, resourcefulness, and rapidity. It may be possible to draw from other sectors to address the components that currently lack metrics, such as the SoVI metric to address resourcefulness, though this metric is currently measured at the county level and may not fully address a highway agency's ability to respond to emergency events.

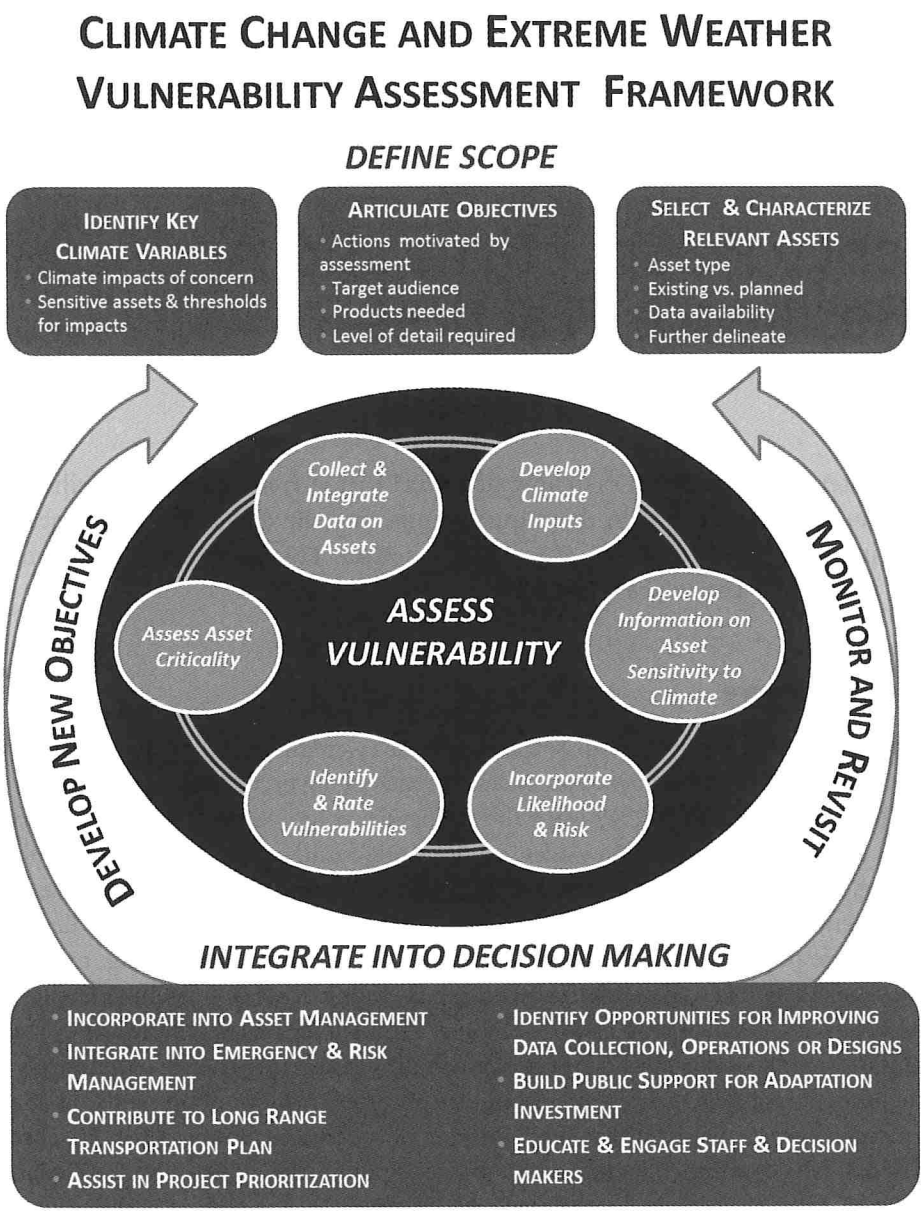
CLIMATE CHANGE AND EXTREME WEATHER VULNERABILITY ASSESSMENT FRAMEWORK
DEFINE SCOPE
IDENTIFY KEY CLIMATE VARIABLES
Climate impacts of concern
Sensitive assets & thresholds for impacts
ARTICULATE OBJECTIVES
Actions motivated by assessment
Target audience
Products needed
Level of detail required
SELECT & CHARACTERIZE RELEVANT ASSETS
Asset type
Existing vs. planned
Data availability
Further delineate
Collect & Integrate Data on Assets
Develop Climate Inputs
Develop Information on Asset Sensitivity to Climate
Incorporate Likelihood & Risk
Identify & Rate Vulnerabilities
Assess Asset Criticality
ASSESS VULNERABILITY
DEVELOP NEW OBJECTIVES
MONITOR AND REVISIT
INTEGRATE INTO DECISION MAKING
INCORPORATE INTO ASSET MANAGEMENT
INTEGRATE INTO EMERGENCY & RISK MANAGEMENT
CONTRIBUTE TO LONG RANGE TRANSPORTATION PLAN
ASSIST IN PROJECT PRIORITIZATION
IDENTIFY OPPORTUNITIES FOR IMPROVING DATA COLLECTION, OPERATIONS OR DESIGNS
BUILD PUBLIC SUPPORT FOR ADAPTATION INVESTMENT
EDUCATE & ENGAGE STAFF & DECISION MAKERS

Figure 6. FHWA Framework for Vulnerability Assessment (FHWA, 2012a).

Frameworks were also introduced to demonstrate potential approaches to measuring system resilience. In some cases, the frameworks address risk assessment as well as system resilience, although others may put an agency on the right path to resilience assessment but require additional assessment beyond vulnerability assessment.

In the next chapter, a review of the current use of resilient practices in state DOTs is provided based on information gathered through a national survey.

CHAPTER 4

Agency Perspectives and Application of Resilience Practices

This chapter provides insight as to how state DOTs are currently applying resilience practices, the methods being used in their applications, and the challenges these agencies are experiencing with implementation of resilient practices. The information is drawn from a survey of state DOTs conducted in the spring of 2017.

Agency Survey

Resilience practices, metrics, models, and definitions were discussed in chapters 1 and 2. To learn more about the use of resilience practices currently being used within state DOTs, a survey was conducted in the spring of 2017 using the online survey tool Survey Gizmo. The survey was developed to better understand how agencies are using resilience practices in their planning, engineering, management, and policy and administration, and the challenges these agencies face in implementing these practices. The survey also provided information to demonstrate which states are performing resilience practices in their planning, engineering, management, and policy making and at what levels they are using these practices (i.e., systemwide, site-specific or asset level, facility level, or modal level). The goal of the survey was to achieve an 80% response rate (40 states) and to collect basic information about the use of resilience practices, as well as to locate potential state DOTs to highlight in case examples, which are presented in chapter 5. The participants were identified through a number of sources, including AASHTO committee membership, TRB committee membership, previous publications from state DOTs, and with help of the NCHRP project panel associated with this study. At the request of the project panel, the survey was also distributed through the National Association of Regional Councils, which represents MPOs and regional councils. Unfortunately, no survey responses were received from this group's members.

The draft survey was sent to the panel members for comment in December 2016 and was later revised to include their comments and subsequently added to the Survey Gizmo website for distribution to the state DOTs in February 2017.

Survey Participation

Given the lack of a home for resilience within highway agencies, the survey was sent to a range of offices across state DOTs, including operations, emergency management, asset management, planning, maintenance, and design. Efforts were made to identify potential survey respondents through AASHTO committee memberships, through presentations and publications made by representatives from state agencies, and with the help of the NCHRP committee panel. Extensive efforts were made to increase survey participation through the identification of alternative

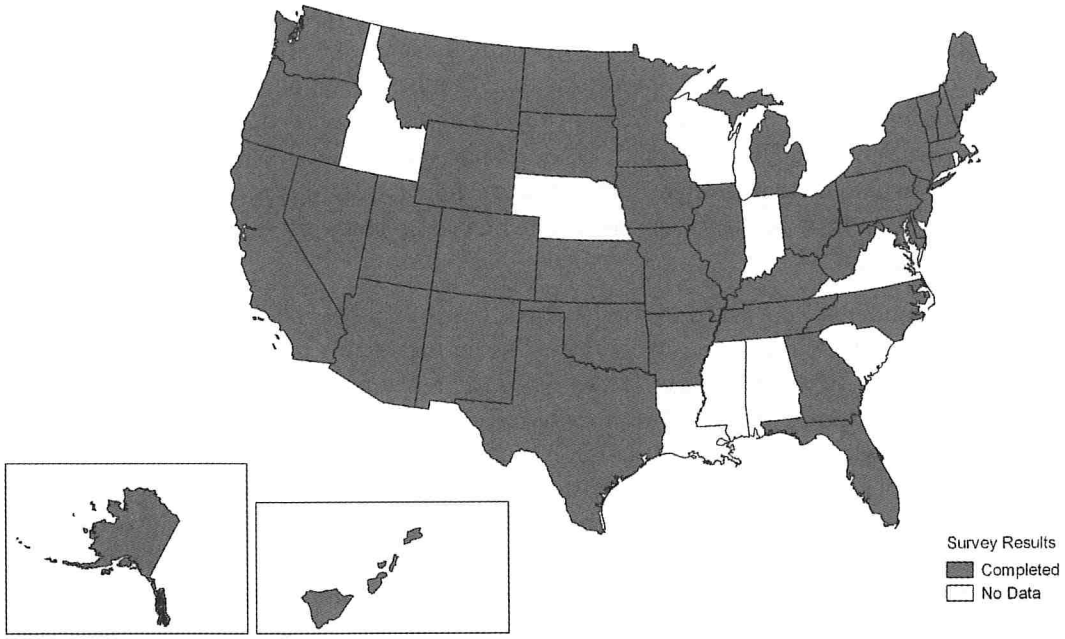

Figure 7. States that completed surveys.

contacts within those agencies who did not respond to the initial survey request, follow-up phone calls, and in-person delivery of requests at various conferences.

The survey was sent to state DOT stakeholders on February 27, 2017, and within the first week, four surveys had been completed. After the first week of distribution, follow up e-mails were sent to the recipients to remind them to complete the survey. The reminder list was updated as surveys were received, and those who completed the survey were removed from the list. In March and June of 2017, the panel was contacted to try to help identify different contacts for the states who did not respond to the initial survey invitation. In total, as of July 12, 40 state DOTs (80%) had responded to the survey, with Maryland completing the survey twice (the DOT and the State Highway Administration), bringing the total number of survey responses to 41. Figure 7 provides a graphical representation of the state DOTs that have submitted completed surveys.

Survey Results

This section of the chapter details the findings of the survey and provides information as to how agencies are currently applying resilience practices in their transportation systems. The first set of questions was used to identify what type of agency was responding, the respondent's area of expertise, and what type of transportation modes the responding agency is responsible for operating or managing. The next set of questions asked the respondents about their current use and understanding of resilience practices. Next, the respondents were asked to detail where/how they are currently using resilience practices within their agency. Finally, the survey concluded by asking the respondents if they were interested in being interviewed for a case example to highlight their use of resilience practices.

The first question of the survey asked respondents what type of agency they were responding from; 100% of the respondents reported being from a state DOT. The next question asked

the respondents to specify their areas of expertise within their organization and select all areas that apply. This information is highlighted in Figure 8. Note, given that the respondents were allowed to select more than one response, the total number of responses exceeds 41 (the total number of completed surveys). A diverse range of responses was received, with "Planning" being the most prevalent, and "Engineering," "Asset Management," and "Policy" closely following. Agency representatives that selected "Other" specified their areas of expertise to include driver licensing, environment and land use, environmental compliance, fiscal, research, and performance management.

Next, respondents were asked to specify what types of transportation modes their agency is directly responsible for operating or managing and were able to select all responses that apply to their agency. As previously described, as respondents were allowed to choose more than one response, the total number of responses exceeds 41. Of the 41 respondents, 41 selected "Roads," 18 selected "Aviation," 16 selected "Transit," 14 selected "Intermodal and Multimodal Facilities," 13 selected "Ports and Waterways," 10 selected "Freight Railroads," 1 selected "Pipelines," and 6 selected "Other," which included ferries, tourist railroads, highways, biking trails, walking trails, and passenger railroads. This information is highlighted in Figure 9 and reflects the wide range of modes that can fall within the responsibilities of any state DOT.

Next, the survey respondents were asked if their agency had developed their own definition for resilience or adopted a definition from elsewhere. Of the 41 respondents, 32 reported they had no definition for resilience, and 8 reported they did have a definition and provided information on adopted definitions. Figure 10 includes a graphical interpretation of the survey responses for this question. Given the relatively new concept of transportation resilience, many DOTs did not report having developed a standard definition for the practice or have yet to adopt a definition from other sources. Table 3 provides the definitions adopted by eight DOTs who reported having adopted a definition of resilience.

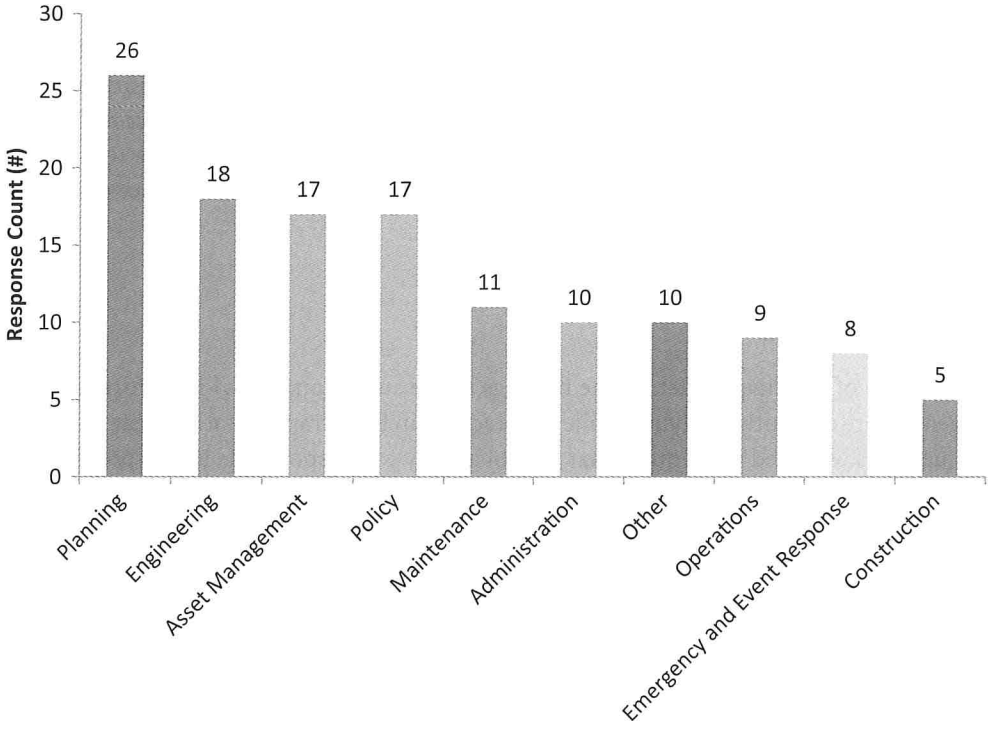

Figure 8. Survey respondents' areas of expertise.

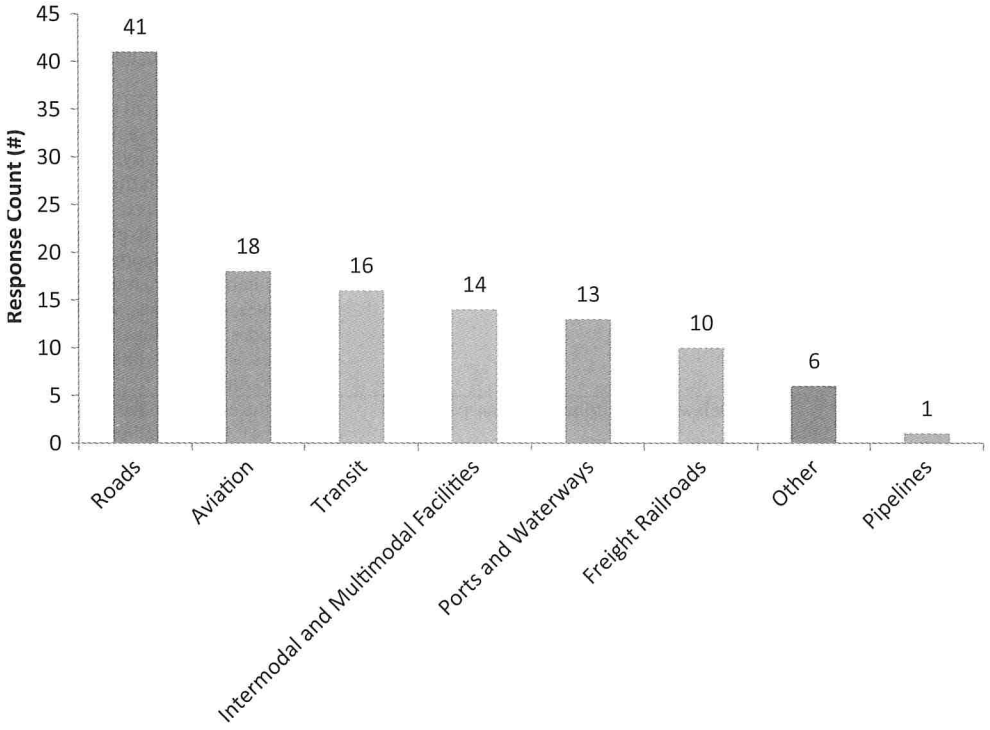

Figure 9. Survey respondents' mode of transportation maintained by responding agency.

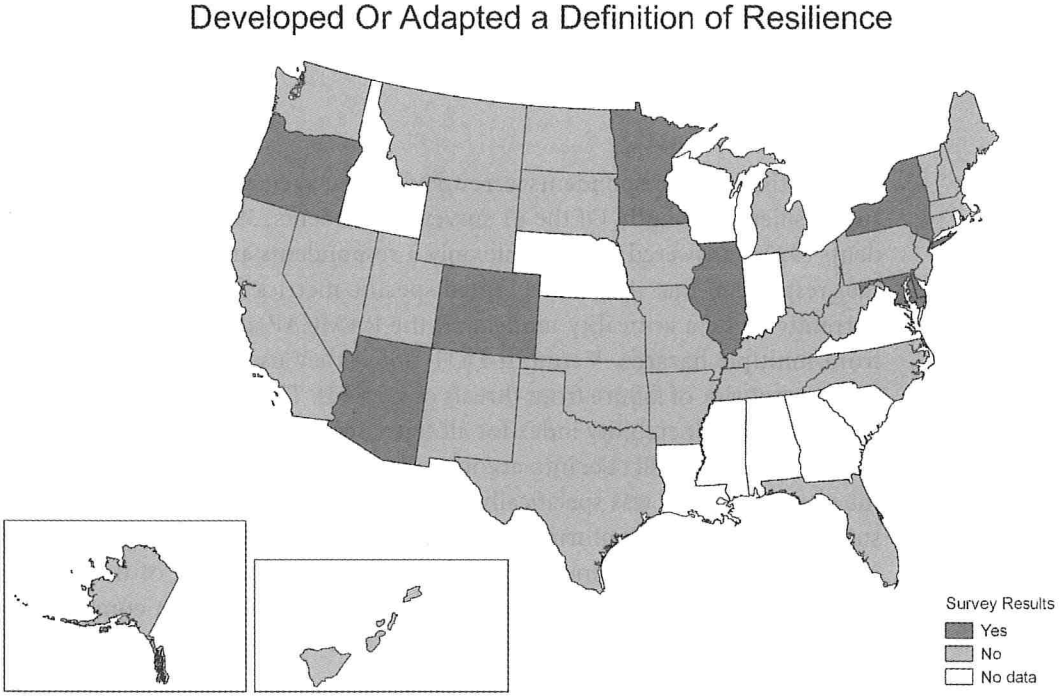

Figure 10. Survey respondent resilience definition.

Table 3. State DOTs resilience definitions.

State Agency	Resilience Definition
Minnesota Department of Transportation	Reducing vulnerability and ensuring redundancy and reliability to meet essential travel needs.
Oregon Department of Transportation	Uses a definition from the ODOT seismic report: "To achieve rapid recovery, require government continuity, resilient physical infrastructure, and business continuity."
Arizona Department of Transportation	ADOT developed its resilience program to support its mission to provide a safe, efficient, cost-effective transportation system that can be compromised from the effects of heat extremes, dust storms, wildfires, flooding, landslides, rockfall incidents, and slope failures, and cope with the ever-growing cost of these threats.
Delaware Department of Transportation	Uses the concept in the Delaware Executive Order 41, which outlines resiliency practices to help mitigate climate impacts and reduce emissions.
Colorado Department of Transportation	Uses a definition provided by the Governor's Resiliency Framework. "The ability of communities to rebound, positively adapt to or thrive amidst changing conditions or challenges – including disasters and climate change – and maintain quality of life, healthy growth, durable systems, and conservation of resources for present and future generations."
New York State Department of Transportation	Uses the recommended guidance provided by the NYS 2100 Commission, which outlines how the state plans to identify areas where further resilience practices are needed.
New Hampshire Department of Transportation	Uses the NAS definition by default, which states "resilience is the ability to plan, absorb, recover and adapt."
Illinois Department of Transportation	Plan and invest in the state's transportation system to ensure that infrastructure is prepared for extreme weather events.

Next, the survey respondents were asked if their agency has specific metrics to assess or measure resilience, or both. Of the 41 survey respondents, 39 answered this question: 36 respondents (92%) answered "No," while only 3 respondents answered "Yes." Of those state DOTs that responded that they had adopted specific metrics for resilience, CDOT noted they are currently using a criticality model and the RAMCAP approach to quantify annualized risk from multiple hazards. Vermont DOT noted they use in-house formulas to decide which assets are at risk of failure from threats or hazards. The Illinois DOT noted they are currently developing a vulnerability index for all state-owned roads, bridges, rail corridors, and operation facilities that will take into account all manmade and natural events. It is interesting that the survey question was specifically asking for resilience metrics, and those respondents that stated "Yes" provided information on how they are calculating risk or vulnerability but did not provide a resilience metric. As noted in the introduction of this synthesis, much work has been done on risk management, but little to date has been completed or implemented on resilience models or metrics or how risk and resilience are related. This is echoed in the responses of the state DOTs.

Next, the respondents were asked if their agency has incorporated resilience practices into their existing programs and to detail the programs that are currently using these practices. Of the

40 survey respondents that answered this question 26 respondents (65%) answered "Yes," while 14 respondents (35%) answered "No." This information is detailed in Figure 11.

When asked which programs are using resilience practices, 70% of respondents noted inclusion of resilience in their project planning and planning programs, 73% of respondents have begun to include resilience in their design methods, and 58% of respondents have included resilience in their asset management programs. For those that chose "Other," responses included emergency response, emergency management, flood recovery, pavement, culvert replacement, and municipal bridge programs. As noted earlier in this chapter, the lack of a true resilience "home" with State DOTs is reflected in the range of areas where state DOTs are addressing resilience. For example, maintenance activities can be used to keep a culvert clear, thus reducing the probability of flooding, thus improving system resilience. Also, agencies, through planning activities and risk assessment, may note a critical redundant route that may need to be upgraded in design standard to accept heavier vehicles of traffic flow, should their main line be closed due to an event. This redundant route may then be addressed in the design process after being programmed in the planning process. Note, respondents were able to select multiple responses, meaning that some states are implementing resilience practices and methods across multiple program areas as shown in Figure 12.

Next, the survey respondents were asked to detail examples of proactive and reactive resilience practices that their agency performs. "Proactive" refers to assessing vulnerabilities and risk for asset improvement to prevent or reduce damage and disruption from future events, while "Reactive" refers to the development of plans for system recovery after an event. The word cloud shown in Figure 13 details the responses received. The word cloud reveals that states are currently focused on both proactive and reactive management of risk, though other words such as "sea-level rise" appear to also reflect emerging efforts for proactive management of system resilience. A range of management areas appear to be engaged in resilience assessment and management, including maintenance, design, emergency response, and asset management.

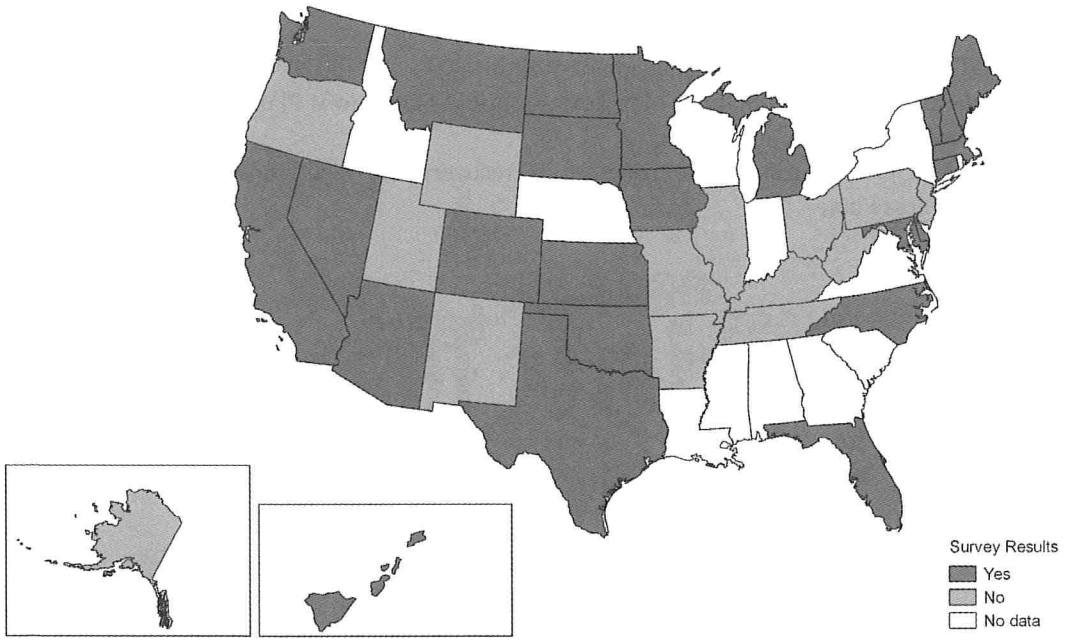

Figure 11. Map of survey respondents who are incorporating resilience into existing programs.

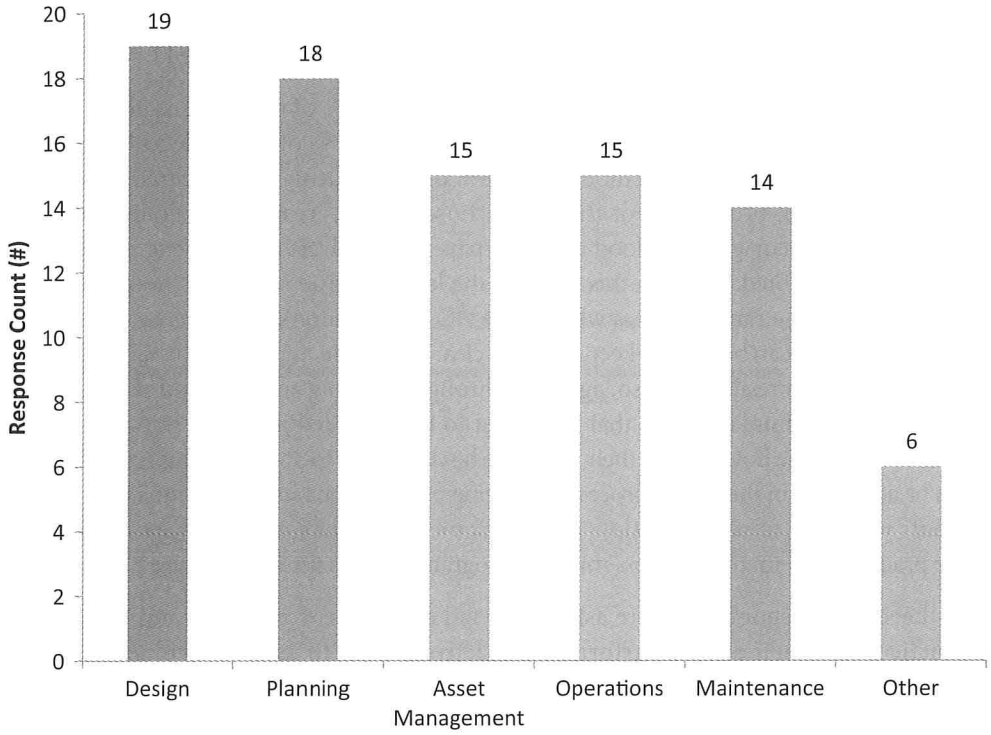

Figure 12. Survey respondents' program resilience.

In addition, terms like "vulnerability" and "mitigation" appear to be more commonplace than in the recent past.

Next, the responding agencies were asked if they currently have a plan to respond to and recover from disruptive events on their system/network or assets. Of the 37 respondents who answered this question, 31 (80%) said "Yes." Of the respondents who said "Yes," some provided examples of their agency's plan. The following are examples:

- ADOT has a full emergency management group;
- Maryland DOT has the State of Maryland Response Operations Plan and the Coordinated Highways Action Response Team;
- Tennessee DOT has an emergency response and recovery plan titled Transportation Emergency Preparedness Plan;

Figure 13. Survey response word cloud.

- Utah DOT uses emergency preparedness efforts to coordinate with other agencies and entities;
- Massachusetts DOT participates in storm-planning workshops and emergency management exercises; and
- New York DOT uses NY Responds website and emergency operations manuals.

Next, the survey respondents were asked if their agency has performed vulnerability or risk assessments, or both, to any particular threats. Of the 41 survey respondents, 22 answered "Yes," 20 answered "In process," and 3 answered "No." The respondents were then asked to provide a list of threats they have analyzed. The answers included climate change, flooding, earthquakes, coastal erosion, funding shortfalls, changes in political environment, terrorism, sea-level rise, fires, rockfall, bridge strikes, and more. The range of threats being analyzed is reflective of the current guidance on risk management for highway assets from FHWA and AASHTO that has cast the net wide in terms of what threats to consider. It would be interesting to learn more about how agencies are predicting some of these threats given the lack of empirical or historical records to establish a probability of occurrence and the results of the event on highway asset or system performance. This information is further detailed in Figure 14.

Next, the respondents were asked at what level their agency performs these vulnerability and risk assessments. Of the 37 respondents who answered this question, 22 (60%) stated they perform them at the system-wide level (e.g., statewide or region wide), 13 (35%) at site-specific or asset level (e.g., HWY 101 at milepost 31; bridge structure F-21-XX), 1 (3%) at the facility level (e.g., Traffic Management Center), and 1 (3%) at the modal level (e.g., a bus-rapid transit system). The respondents were then asked to select all assets where they perform vulnerability or risk assessments, or both. Given the data requirements for pavement and bridge management systems, it is not surprising that these two asset classes ranked high in terms of assets being analyzed for vulnerability or risk assessments. Culverts and drain pipes were also noted to be assessed for vulnerability or risk assessment by many state DOTs. The range of assets being assessed [including intelligent transportation systems (ITS), tunnels, signs/signals, and facilities] reflects the emerging desire to understand more about system vulnerability and potential risk.

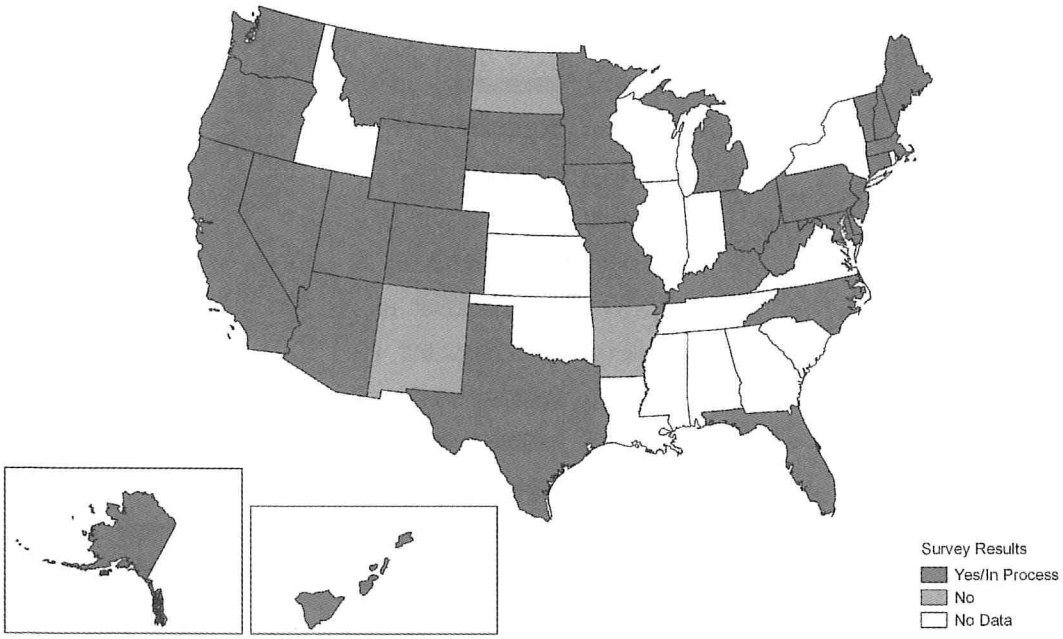

Figure 14. Map of survey respondents that have performed vulnerability or risk assessments.

This information is presented in Figure 15. For those that chose "Other," responses included evacuation routes, back-up power, communications, fueling, ferries, rail corridors, pump stations, and slopes.

Next, the survey respondents were asked if they have guidance or procedures in place to incorporate consideration of climate change vulnerability in planning, project development, and engineering design. Of the 39 respondents, 26 stated they have none, and 13 stated they have guidance. The respondents were then asked to detail what types of guidance their agency is currently using. New York, Pennsylvania, Hawaii, and Maine are all currently in the process of developing guidance. Florida DOT noted that they have incorporated climate change vulnerability in their roadway design manual. Also, the Maryland State Highway Administration noted that they published a Climate Change Adaptation Plan with Detailed Vulnerability Assessment in October 2014.

Next, the responding agencies were asked if they used any specialized models/software to incorporate and/or evaluate resilience. Some respondents provided examples of the models/software they use.

- Florida DOT developed a sea-level risk sketch planning tool based on the U.S. Army Corps of Engineers (USACE) and the National Oceanic and Atmospheric Administration/National Climate Assessment sea-level rise scenarios.
- Ohio DOT uses the FHWA Vulnerability Assessment Scoring Tool.
- Colorado DOT uses the Risk and Resilience Analysis based on RAMCAP Plus framework. This is a 7-step repeatable, data-driven model for risk and resilience assessment of infrastructure published by ASME.
- Caltrans noted multiple models currently in use, including the U.S. Geological Survey (USGS) Coastal Storm Modeling System, a USACE Sea-Level Change Curve Calculator, and the CalFIRE Wildfire Model. Caltrans noted extensive GIS modeling to support the use of these models.

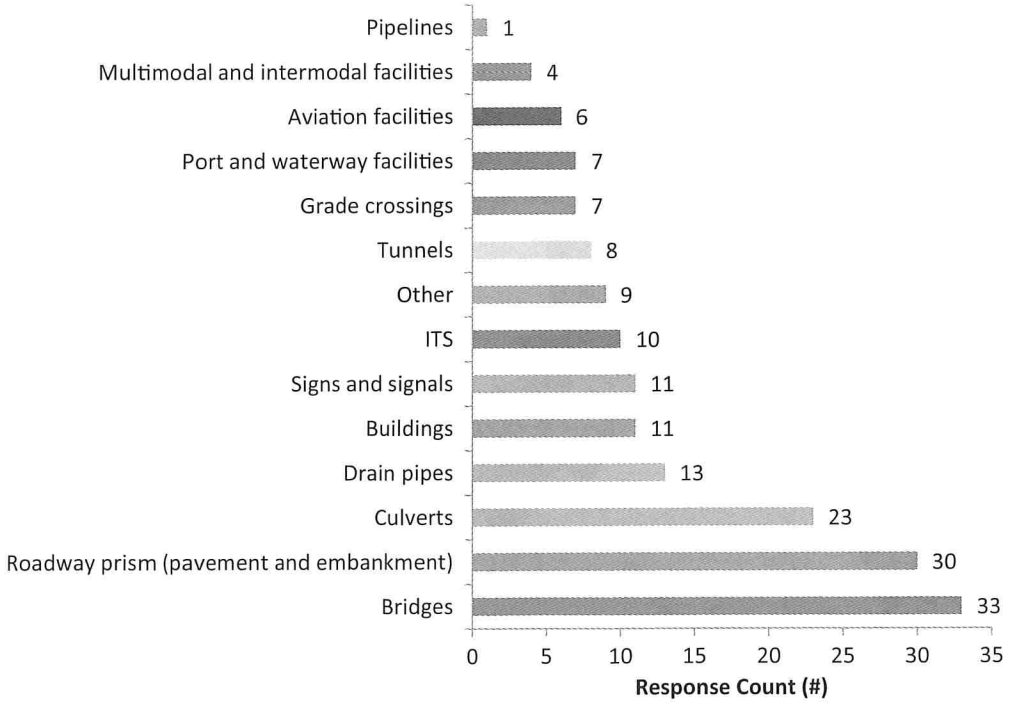

Figure 15. Vulnerability and risk assessments by asset.

The responding agencies were then asked to select areas where they would like to gain additional information, best practices, and training. This information is presented in Figure 16. Of particular note is the high response rate requesting additional information on resilience metrics and methods in which 87% of respondents are requesting additional information. In addition, information is requested that will support resilience modeling including asset criticality assessment, deterioration curves, asset vulnerability, and expected benefits from mitigation measures. This may imply that agencies desire to better understand their system resilience and anticipated performance under threats but may not yet have the information needed to accomplish this analysis.

Next, the responding agencies were asked if they incorporate benefit–cost analysis into their transportation resilience analysis. Of the 39 respondents that answered this question, 32 said "No," and 7 said "Yes." This is an important point given the acceptance of economic analysis of investments that go above and beyond standard design practices. Without fully understanding the benefit of resilient practices, it will be difficult for staff to justify additional expenditures to increase system resilience. As noted in the previous question regarding additional information that is requested of participants, additional information on the expected benefits from mitigation measures is needed as well. Without this information, it will be difficult for agencies to perform benefit–cost analysis to economically justify investments in resilience.

The responding agencies were then asked if they allocate or set aside funding to improve transportation resilience through any of the following: maintenance, operations, planning, design, and construction of projects. If they said yes, the agencies were asked to provide revenue sources that they use for this funding. Some of the funding sources that were highlighted included FEMA programs, FHWA programs such as the ER program and the National Highway Performance Program (NHPP), the BRIDGE NY program, the Regional Greenhouse Gas Initiative, and state resources. Of note is the use of emergency response funding sources to improve system resilience through FEMA and FHWA ER programs.

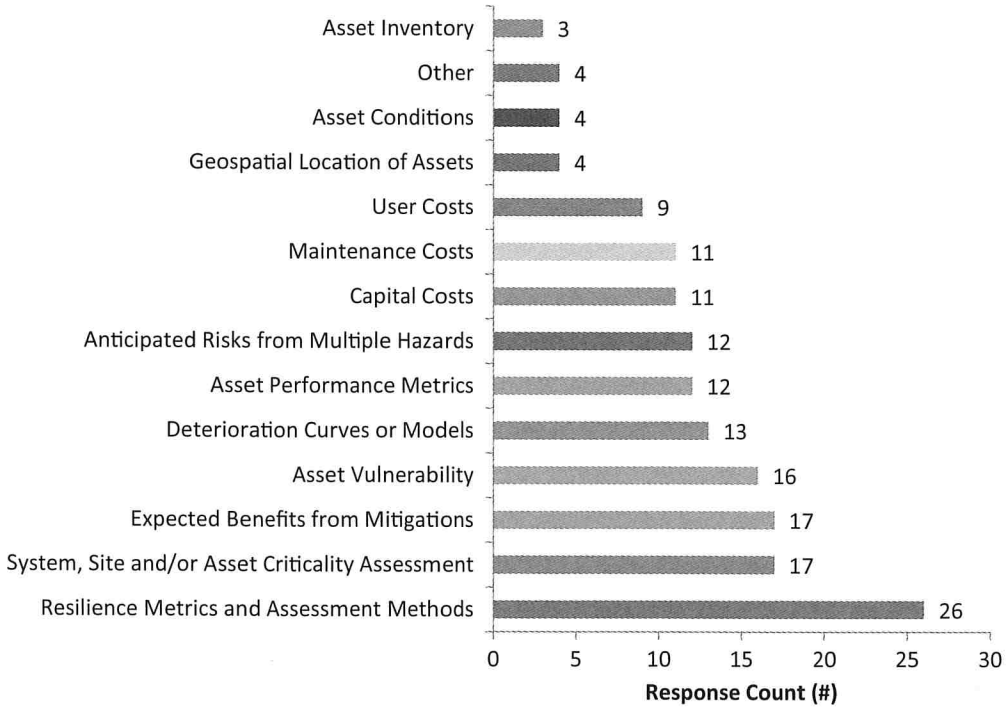

Figure 16. Where survey respondents would like additional information.

Summary

A survey was conducted with 40 state DOTs on the topic of resilience. Questions were aimed at gaining a better understanding of the incorporation of resilient practices and policies within their agencies.

A range of departments within the state DOTs responded to the survey, including maintenance, operations, planning, engineering, and asset management. Some agencies appear to be embracing resilience and have begun to shape their own definitions of what resilience will mean or does mean to their agency. Eight respondents provided details on their agency's definition of resilience. Climate change and extreme weather appear to be the primary focus of many of these definitions, although there is some mention of being able to absorb and adapt to events.

Over half of the respondents noted that their agency is incorporating resilience into their programs including planning, asset management, operations, maintenance, and design. In addition, they are addressing resilience at a range of levels from system to asset level and beginning to conduct vulnerability or risk assessments on specific assets, with bridges and pavements being the most prevalent followed by culverts and drains.

Of note is the desire for additional information regarding resilience modeling, metrics, and expected benefits of mitigation measures. Survey respondents requested additional information related to several variables and inputs needed to model resilience including the metrics themselves, methods to capture asset criticality, deterioration curves, asset vulnerability from applicable threats, and anticipated performance of mitigation measures.

Of the survey respondents, a few noted their willingness to participate in a case example. The following pages outline five case examples that reflect efforts underway in three departments of transportation, including Arizona, Colorado, and Delaware, and two case examples developed to highlight resilience efforts underway at PANYNJ and GTC, which is an MPO in the State of New York.

CHAPTER 5

Case Examples

This chapter documents five case examples related to the incorporation of resilience practices by state agencies. Survey respondents were asked if they would like to showcase their agency's resilience practices through the development of case examples. The case examples were developed by using information from the survey, as well as in-depth interviews with staff. The case examples include the following state agencies:

- ADOT,
- CDOT,
- DelDOT,
- PANYNJ, and
- GTC (MPO).

Arizona DOT Case Example

ADOT was chosen as one of the case examples for this report because of their incorporation of resilience practices at different agency levels, use of technology, and willingness to participate. Based on an interview with Steven Olmsted, Innovative Programs Manager, Infrastructure Development and Operations at ADOT, information regarding the agency's projects for resilience, extreme weather and climate adaptation, sustainable transportation, and ADOT/USGS partnerships was gathered and summarized. Mr. Olmsted is responsible for developing Infrastructure Health and Sustainability initiatives along with resilience and climate adaptation projects.

ADOT is a multimodal agency responsible for over 30,000 maintenance lane miles (of the 140,000 state maintenance miles); 4,700 bridges (of the 7,800 state bridges); seven districts; 1,500 facility buildings; the Grand Canyon Airport; and the Department of Motor Vehicles. The agency's mission is "to provide a safe, efficient, cost effective transportation system" (Arizona Department of Transportation, Online). The strategic focus areas of the agency are safety, workforce development, infrastructure health, innovation, and financial resources.

Since 1966 Arizona has had 195 declarations of emergencies and currently has five federal disasters remaining in the open status (Arizona Department of Emergency and Military Affairs, Online). The five open federal disasters resulted from a range of events, including winter storms and monsoon storms that caused flash flooding, damaging winds, and hail. The major threats that ADOT has to manage include the effect of heat extremes, dust storms, wildfires, flooding, landslides, rockfall, and slope failure (Arizona Department of Transportation, Online).

In 2013, ADOT published a report based on a Preliminary Study of Climate Adaptation for the Statewide Transportation System in Arizona. In 2015 this study was followed by the agency's managed transportation infrastructure and state-specific Extreme Weather Vulnerability

Assessment included in FHWA's Climate Change Resilience Pilot Program [Arizona Department of Transportation, 2013 and 2015; FHWA Online (a)]. The vulnerability assessment focused on the interstate corridor conformed by I-19, I-10, and I-17 and included climate-related threats such as extreme heat, freeze–thaw, extreme precipitation, and wildfire. The project resulted in a qualitative assessment of the interaction between extreme weather and climate change with various land use and transportation facility types.

Based on these previous efforts, ADOT established the Resilience Pilot Program as an outgrowth of their Sustainable Transportation Program and subsequently operationalized a full resilience program (RP) in October 2015. The primary mission of the RP was to strike a balance between predictable asset deterioration curves and erratic extreme weather events. To do this, the RP is focusing its efforts on the following:

- Centralizing efforts to address erratic extreme weather events and their effects on assets within this office;
- Introducing extreme weather adaptation to the agency and engineering design processes;
- Establishing an understanding of transportation asset sensitivity to extreme weather events;
- Downscaling climate data to the transportation asset level for analysis;
- Incorporating actions into the decision-making process, including planning, design, construction, maintenance, and operations; and
- Capitalizing on available partnerships, technologies, and tools (Olmsted et al., 2016).

Capitalizing on partnerships, ADOT has established a working relationship with USGS through 2020 that provides $1 million a year to adapt digital, numerical, and dimensional data suitable for ADOT consumption and use (Olmsted et al., 2017). As part of this partnership, ADOT/USGS developed projects in December 2015 to study Arizona's state route (SR) 93 roadway expansion and realignment and SR 160 Laguna Creek Bridge Scour.

ADOT has successfully worked with analysts from USGS to better understand the potential flow and path of extreme rain events and how those flows may affect ADOT assets. As was noted by Steven Olmsted of ADOT, often hydraulic analysis is limited to right-of-way boundaries, and USGS is able to model accumulation and flow of rainfall much further upstream of ADOT assets, allowing for a better understanding of the potential effect of storms. The RP has expanded this work and is now incorporating advanced technologies, including direct storm monitoring and data collection, post-storm indirect event monitoring and data collection, and next generation LiDAR and drone data collection capabilities to its modeling capabilities through its partnership with USGS. This approach is allowing ADOT to better plan for and respond to flooding, overtopping events, and extreme weather events. They are also working to incorporate this new information into stormwater management practices, scour modeling, drainage location, design, and construction. From a policy standpoint, ADOT believes that this effort better aligns the agency to respond to federal extreme weather regulatory activities and informs the National Environmental Policy Act process and wetlands delineation (Olmsted et al., 2017).

ADOT has begun to incorporate their efforts into specific project designs. In October 2015, ADOT pilot tested the Resilience Investment Economic Analysis on a pavement preservation project on SR 191 with an estimated preliminary budget of $5 million. Initially the project was not to address drainage, but engagement of the RP staff helped flush out the expected return on investment and increased facility resilience through the replacement of multiple drainage structures. Inspection revealed that 61 of the 86 corrugated metal pipe drainage structures had suffered 25–100% degradation due in part from erosion and slope instability. The RP staff worked with district staff to gather information regarding costs associated with replacement of 31 drainage structures to further extend the project life cycle, address regulatory considerations, and lower the probability of water undermining the embankment, pipe washout, overtopping of the road due to buried or lower capacity, and end-of-life drainage structure capabilities. In the end

the investment was estimated to increase the project budget by $300,000 in order to meet the objectives set out by the RP staff.

In 2016, ADOT initiated another project referred to as the Laguna Creek project in which data from the USGS Arizona Water Science group provided ADOT with real-time storm monitoring and data collection; post-storm event monitoring and data collection; and next generation hardware/software and surface water flow data, including LiDAR, drone data, rapid deployment streamgage, non-contact velocity sensors, video camera and particle tracking data collection, and 3D land surface models. As a result of this analysis, several design recommendations were made, including installation of spur dikes along Laguna Creek Bridge, channel improvements to increase the hydraulic performance of a bridge in the project area, and riprap spur dikes to protect bridge abutments from 500-year events.

All of the past resilience projects helped to identify lessons learned and areas of improvement for incorporating resilience practices at the agency. Some of the key lessons learned include the following:

- Challenges for data acquisition (e.g., the need for high, special resolution of climate data and processing tools).
- An understanding of data uncertainty within climate projections and vulnerabilities.
- The need to balance resources with project scope.
- The need of internal and external stakeholder input when conducting assessments.

ADOT sees the efforts of the RP touching on funding and tool development, its 5-year construction program, emergency response, roadway/bridge/drainage decisions, geotech, and more. The commitment to the program has helped to establish a continuity of the program that will improve its chances of success and incorporates different agency areas such as planning, design, construction, operations and maintenance taking advantage of available technologies, tools, and partnerships.

Colorado DOT Case Example

CDOT was chosen as a case example because of the experience the agency has had with the incorporation of resilient practices into their designs during the 2013 flood recovery effort. In addition to the 2013 major flooding event that resulted in over $750 million in highway asset damage, Colorado has experienced 10 major disaster declarations in the past 20 years with most of the declarations being related to floods, mudslides, landslides, wildfires, and tornadoes (FEMA, Online).

Following the most recent floods and fires in the state, the governor formed the Colorado Recovery Office in 2013, later renamed the Colorado Resiliency and Recovery Office (CRRO), which seeks to improve resiliency planning, development, and implementation through collaboration, coordination, and outreach to local, state, federal, and private partners. With support from the CRRO, the Colorado Recovery and Resiliency Collaborative was formed with representatives from local, state, and federal agencies whose focus is on working to improve communications and coordination between organizations involved in Colorado's flood and fire recovery. The vision of this group is to "Create, improve and promote resilient communities through mentorship and guidance in recovery." In support of that vision, the CRRO has published reports, including *Putting Disaster Recovery Lessons Learned Into Action*, a report that includes all the lessons learned after the 2013 floods and fires in the state, and the *Local Government Guide to Recovery*, a planning tool to help agencies develop emergency management programs from pre-event planning to emergency recovery (Colorado Recovery and Resiliency Collaborative, 2015 and 2017).

Another important effort from the CRRO was the publication of the *Colorado Resilience Framework* in May 2015 as a long-term commitment to a more resilient state and statement of partnership among many sectors, including federal, state, and local agencies; non-profits; and business and community members (State of Colorado, Online, b). The resilience framework integrates six major sectors: economic, community, health and social, housing, watershed and natural resources, and infrastructure. One of the main strategies from the framework for the infrastructure sector is the assessment of infrastructure risk to determine a comprehensive approach to hazard mitigation, along with the development of policies to integrate resilience approaches at the design and construction levels.

In addition to the efforts underway through the CRRO, CDOT has been proactively seeking resilient solutions to damage incurred during the 2013 flood event. In response to the event, CDOT established a flood recovery office (FRO) to coordinate and oversee recovery and resilience efforts (CDOT, Online, a). As part of this effort, CDOT adopted a process for their flood ER program, based on risk assessment, to justify resilience and mitigation projects at locations that suffered severe damages from the 2013 floods. CDOT adopted the ASME Innovative Technology Institute's RAMCAP Plus framework to assess future risk with existing or resilient design alternatives. RAMCAP Plus was developed in response to the terrorist attacks of September 11, 2001. Initially focused on terrorist or directed threats, it has evolved to include all physical threats, including those related to natural threats such as weather-related hazards and seismologic events. Since 2002, many hundreds of nationally recognized experts; scientists; engineers; industry leaders; academics; and federal, state, and local government officials have been involved in continual development of the RAMCAP Plus risk and resilience framework (AWWA Staff, ASCE/AWWA Committee, 2009). RAMCAP Plus has the additional advantage of more than a decade's worth of application across diverse sectors of the U.S. economy, and it is also well known among federal agencies. As an example of applicability of this framework in another sector, AWWA developed a set of standards (J100-10) for all-hazards risk and resilience analysis and management based on this framework (AWWA Staff, ASCE/AWWA Committee, 2009).

Since 2013, CDOT has tailored the generalized RAMCAP Plus^{SM} methodology to a sector-specific analysis framework, referred to as risk and resilience for highways process. Applying this framework, the likelihood and intensity of each specific threat for each asset, the system, and related services is calculated using the following risk equation:

$$R = C \times V \times T$$

where R (risk) and C (consequence) are measured in dollars; V (vulnerability) and T (threat) are each expressed as probabilities.

The expected consequences from each threat depend on the particular asset and threat under analysis, and it is calculated as the worst reasonable case for the event. These consequences are determined based on historical data and agency experts input. Consequence can be categorized as asset replacement cost, user costs (i.e., wages and vehicle running costs), human fatalities, injuries, and environmental impacts. The vulnerabilities of the asset or system are calculated as the probability to experience the expected consequences, which are also derived from literature, historic and empirical data, and stakeholder input. In addition, threat is calculated as the probability of a particular event to occur, and it is derived from historic and empirical data. As a result of the product of these three factors, risk is calculated as the expected annual monetary losses from applicable threats.

This formula makes it possible to weigh alternatives for managing risk and improving resilience. Benefits of potential mitigation measures can be assessed in terms of risk avoidance or increased resilience. Risk, mitigation, and resilience can then be incorporated into the prioritized annual

investment decisions, aligning the risk and resilience assessment outcomes with an agency's overall performance goals.

Figure 17 provides an overview of the risk and resilience for highways process adopted by CDOT from the RAMCAP Plus process.

From its inception, one objective of the FRO was to adapt the RAMCAP Plus methodology to build back better. The model was used to quantify expected losses, evaluate consequences, and develop mitigation alternatives related to the flood. This approach was informed by the 1976 Big Thompson River/Cache la Poudre River floods, previous severe flooding in the same area as the 2013 floods (Shroba et al., 1979). Recovery decisions were guided by the definition of risk adopted by CDOT: "Risk is the expected annualized monetary loss of an asset from any defined threat that reflects the likelihood of that threat as well as the vulnerability of that asset to that threat" (Flannery et al., 2014). This methodology linked risk and resilience to risk-based asset management, quantifying results in terms of expected annual monetary losses. Models used in CDOT's risk and resilience analysis reflect the following:

- A probabilistic threat analysis,
- The asset condition,
- The threat geographic location and context,
- The interdependency of nearby assets,
- Vulnerability, based on asset condition and mitigation strategies,
- Asset engineering design standards, and
- Post-event emergency repairs and permanent repairs.

Risk- and resilience-based asset management decisions were developed from empirical data derived from various national databases maintained by organizations such as the USGS, FEMA, and the U.S. Department of Agriculture, as well as by regional data generated in response to the Colorado floods (e.g., LiDAR). Flood recovery decisions took into consideration the design standard of the asset, the age of the asset, the location of the asset, and the interdependency of assets with the network. Decisions reflect the interdependency between pavement, roadway prism, channel and bridge design, and mitigation strategies. Benefit–cost metrics and the annual reduction in risk and annual resilience metric provided by each mitigation strategy were calculated.

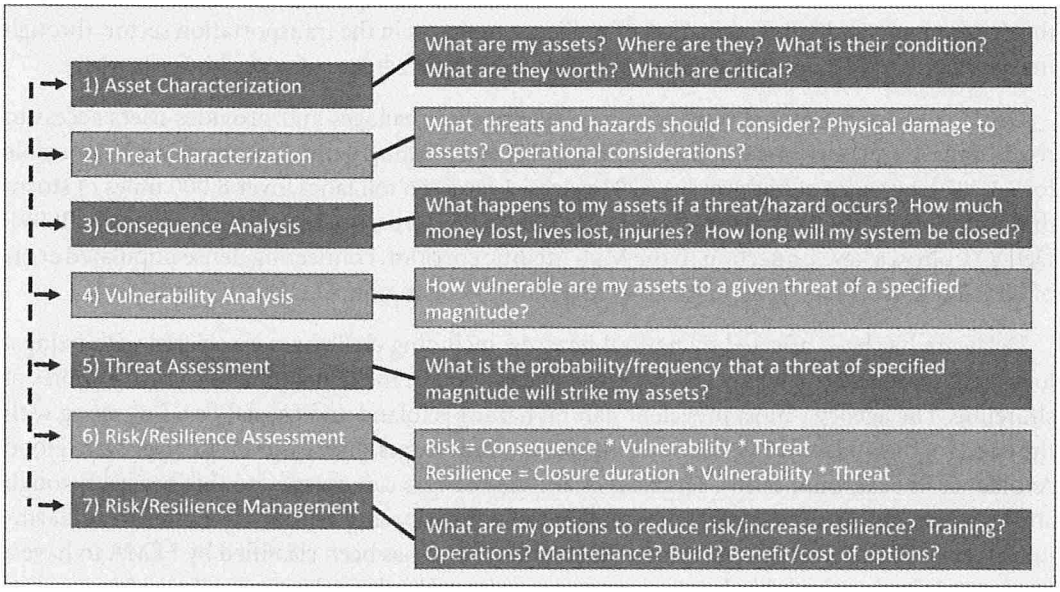
1) Asset Characterization
What are my assets? Where are they? What is their condition? What are they worth? Which are critical?
2) Threat Characterization
What threats and hazards should I consider? Physical damage to assets? Operational considerations?
3) Consequence Analysis
What happens to my assets if a threat/hazard occurs? How much money lost, lives lost, injuries? How long will my system be closed?
4) Vulnerability Analysis
How vulnerable are my assets to a given threat of a specified magnitude?
5) Threat Assessment
What is the probability/frequency that a threat of specified magnitude will strike my assets?
6) Risk/Resilience Assessment
Risk = Consequence * Vulnerability * Threat
Resilience = Closure duration * Vulnerability * Threat
7) Risk/Resilience Management
What are my options to reduce risk/increase resilience? Training? Operations? Maintenance? Build? Benefit/cost of options?

Figure 17. Risk and resilience for highways adapted from RAMCAP Plus.

Building on its experience with the risk and resilience for highways approach, CDOT initiated a pilot program in August 2016 for asset management for the I-70 corridor across the entire state (approximately 470 miles in length). The project addresses proactively the quantification of risk and resulting system resilience of relevant physical threats on the corridor. The project is conducting an all-hazards analysis for most assets in the corridor, including the following hazards: bridge strike, rockfall, flooding (including scour, overtopping, and debris flow), landslides, avalanches, wildfires, and direct threats (manmade). In addition, the assets analyzed included bridges, roadway prism, culverts, walls, tunnels, and ITS devices.

The project was completed in November 2017 and engaged staff from all five regions of CDOT through a working group comprised of 12 staff members with a range of expertise, including project engineers, operations engineers, transportation planners, asset managers, and maintenance supervisors. In addition, an executive oversight committee was engaged in the project to oversee the project findings and to help strategize as to the potential uses of the information being provided through the project.

Findings of the project included a criticality model developed with input from CDOT staff to help understand which assets along I-70 are most critical to corridor resilience and annual risk calculations that reflect owner and user costs (where user costs reflect the redundancy and additional travel time and distance for detours around closures). Risk calculations were developed at the individual asset level to reflect the vulnerability of each asset to each applicable threat in situ. Annual risk information can be provided at the individual asset level or asset class level or categorized by threat type.

CDOT has engaged their commission in the study and is currently considering next steps to expand the pilot study to additional corridors and a range of program areas, including planning, resilient design, risk-based asset management, maintenance, and operations.

Delaware DOT Case Example

DelDOT has been using resilience and sustainability practices in their agency for the past 10 years. These initiatives have been incorporated at different agency levels such as planning, engineering and design, operations, and policy. An interview with Dr. Silvana Croope (8 May 2017) from DelDOT offered an overview of this effort. Dr. Croope has an extensive knowledge on the development and implementation of resilience practices in the transportation sector, through the development of a decision support system to improve resilience of critical infrastructure.

DelDOT is a multimodal transportation agency that manages and provides users access to roads, rails, buses, airways, waterways, bike trails, and walking paths. The agency is responsible for 13,507 lane miles of highways, 1,520 bridges, 1 ferry, 56 toll lanes, over 8,000 miles of storm drains, 93 buildings, and many other assets (Delaware Department of Transportation, 2009). DelDOT offers a key connection to the Mid-Atlantic corridor, connecting dense populated areas of New York; New Jersey; Pennsylvania; Maryland; Washington, D.C.; and Virginia.

Delaware has been affected by natural hazards, including challenges associated with being a low-lying coastal state (the lowest average land elevation in the United States) with 381 miles of shoreline. The agency's most prevalent natural hazard is inland and coastal flooding along with the effects of high tides, winds, salt water intrusion, storm surges, and sea-level rise (Delaware Flood Avoidance Workgroup, 2016). Hurricanes and nor'easters can exasperate this hazard through strong winds, storm waves, and high tides that cause flooding and erosion to coastal areas. Earthquakes also affect the northern region of Delaware, which has been classified by FEMA to have a moderate seismic risk. Sinkholes are also being monitored by the Delaware Geological Survey and are considered a hazard in the state, especially in regions where the geomorphologic conditions

are present (University of Delaware, n.d.). In addition, more than 17% (331 square miles) of the state's land area, including 6,000 road miles and over 18,000 structures, fall into FEMA's special flood hazard area [1% annual chance of flooding or 100-year flood insurance rate maps (FIRMS)] (Delaware Flood Avoidance Workgroup, 2016).

FEMA has recorded 16 major disaster declarations in Delaware since 1962, including the most recent winter storm and flooding in 2016 and Hurricanes Sandy and Irene in 2012 and 2011, resulting in five emergency declarations having been issued since 1993. Most of these major disasters and emergency declarations have been related to hurricanes, flooding, and major storms, with a few related to snowstorms, blizzards, and droughts (U.S. Department of Homeland Security, Online, b).

Due to the exposure of Delaware transportation assets and the effect of climate change, DelDOT has been studying and implementing many strategies to assess and reduce the vulnerability of state assets and increase the resilience of their systems and networks. Climate adaptation and resilience are terms widely used among Delaware state agencies in their efforts to avoid disruptions to their critical systems and networks. DelDOT defines resilience as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (The National Academy of Sciences, 2012). Currently, DelDOT has not developed or adopted any formal resilience metrics.

To assess the resilience of DelDOT's systems and networks, DelDOT participated in one of the first vulnerability assessments for the State of Delaware for sea-level rise as a collaborative effort of multiple state agencies (Delaware Coastal Programs of the Department of Natural Resources and Environmental Control, 2012). Results of this assessment were released in July 2012, and a guide was published in 2013 with recommendations for state agencies, local governments, businesses, and individuals for building capacity for adapting to sea-level rise (Delaware Coastal Programs of the Department of Natural Resources and Environmental Control, 2012; Delaware Sea-Level Rise Advisory Committee, 2013).

As follow-up to this document, Delaware organized a workshop in March 2014 to bring together stakeholders from different areas to develop implementation actions for sea-level rise adaptation (Delaware Department of Natural Resources and Environmental Control, 2014). During the workshop, a Transportation and Infrastructure Workgroup was formed to focus on recommendations, particular to transportation assets, and the concern from transportation agencies regarding the management and maintenance of their infrastructure. DelDOT completed an analysis regarding legal issues of infrastructure disinvestments and completed a bridge rating based on sea-level rise. Some of the recommendations in this guide include improved coordination of permit decisions for adaptation projects among federal, state, and local officials and incorporation of sea-level rise into planning, policy, and budgeting levels.

At the policy level, Delaware has released multiple state policies to reinforce federal initiatives on the implementation of resilience practices. In 2011, a law (Senate Bill 64) addressing statewide flooding risk was signed by the governor to address Delaware's coastal and inland flooding vulnerability and to identify higher floodplain and drainage standards. Also, a sea-level rise adaptation policy was developed to serve as a pilot for future initiatives and statewide application. In 2013, the governor of Delaware created the Governor's Committee on Climate and Resilience and signed Executive Order 41 (EO 41): *Preparing Delaware for Emerging Climate Impacts and Seizing Economic Opportunities from Reducing Emissions* (State of Delaware, 2013). EO 41 builds on previous policies and requires state departments and agencies to incorporate measures and initiatives to prepare for emerging climate impacts and to incorporate sea-level rise scenarios and increased flood heights into construction projects and long-range planning. Three workgroups were created under the secretary's direction, and the work and collaboration of these workgroups was summarized on the Delaware climate framework approved by the

governor in December 2014 (Cabinet Committee on Climate and Resilience, 2014). The climate framework proposed a series of 150 recommendations to state agencies related to regulations, policies, mitigations, and implementation plans to reduce state greenhouse gas emissions and to improve state preparedness and resilience to climate change.

In March 2016, a manual titled *Avoiding and Minimizing Risk of Flood Damage to State Assets: A Guide for Delaware State Agencies* was released to help state agencies in this process (Delaware Flood Avoidance Workgroup, 2016). In addition, 11 existing policies and programs were identified where flood risk reduction practices at the project planning, design, and funding programs levels, among others, should be incorporated (Delaware Flood Avoidance Workgroup, 2016). Along with this guide, many other projects have been developed to assess the vulnerability and resilience of Delaware to flooding and sea-level rise. A key component of asset vulnerability assessment is the development of the state climate change scenarios and projections. In 2014, a Climate Change Impact Assessment was developed for the State of Delaware releasing historic climate change trends and future climate change projections for temperature and precipitation (Delaware Department of Natural Resources and Environmental Control Division of Energy and Climate, 2014). In this assessment, there is a study of the effects of changes in precipitation, temperature, and sea-level rise in different sectors, including infrastructure.

In addition to the assessment of climate change scenarios and the resulting consequences on the resilience of the state transportation infrastructure, the development of mapping tools for flood risk identification has been an important factor in determining the vulnerability of transportation assets. With the collaboration of engineering consultants and state agencies, three types of maps were developed for Delaware that can be used for flood risk identification: the FIRM, normally used and developed by FEMA; the Sea-Level Rise Inundation Map, created by the Department of Natural Resources and Environmental Control Delaware Coastal Programs in 2009 to estimate potential inundation from sea-level rise; and the Flood Risk Adaptation Map, which is the only one of the three maps that combines the risk of sea-level rise and coastal storms. Only the FEMA maps are regulatory, but the three maps can be used as planning tools to identify areas of potential flood and inundation risks. All three maps have their limitations and uncertainties and are mainly used as screening tools to identify sites with potential vulnerability to flooding.

To support the use of these additional data sets and mapping, DelDOT has invested to improve their asset inventory, bridge design manual, data collection systems for roadway weather information, monitoring of traffic flow, and roadway conditions and traffic operations. Some of the initiatives include projects to develop an inventory of their roadways using LiDAR, the addition of sensors to measure water levels, speed and volumes to collect and analyze flood data and support climate analysis, improvement of their data analysis capabilities and GIS, use of risk assessment tools such as mapping tools and an improved data exchange to Hazus model (FEMA), and scenario-based debris estimates, among many other initiatives (Cabinet Committee on Climate and Resilience, 2014). To document the progress toward these recommendations along with challenges and identified required resources to achieve these goals, DelDOT is currently developing a Strategic Implementation Plan for Climate Change, Sustainability, and Resilience for Transportation.

Some of the challenges faced by DelDOT to achieve its resilience goals include funding, especially for projects not mandated by regulations; lack of training for climate change impacts and its effects on agency investments; lack of knowledge of available tools; lack of clear direction and training regarding climate change; and the need to coordinate across divisions, districts, other state agencies and establish a holistic regional and subregional coordination. Related to funding challenges DelDOT faces is the revision of the need, or not, for transportation catastrophe insurance in order to be able to fund mitigation alternatives to recover from catastrophic events (Croope, 2017).

Some of the next steps for DelDOT's work on resilience include the creation of an asset inventory that any other state agency can use and update, utilization of new 3D models and simulation, development of a statewide transportation risk map, and exploration of different funding opportunities to support resilience initiatives. These efforts will help policy makers, designers, planners, emergency response managers, and others to make better decisions when incorporating adaptation and resilience practices at different levels. To overcome some of these challenges, an ongoing effort is working with support from the National Institute of Standards and Technology to evolve transportation resilience in consideration to the community and adopt a programmatic and project level economic assessment (Croope, 2017).

Some of the challenges DelDOT faced during the implementation of their Hazus risk assessment and loss estimation tool on their projects include the ability to input local transportation data. As part of a collaboration with the Delaware Emergency Management Agency, DelDOT got into an agreement with the University of Delaware to build a user-friendly solution to enabling all Hazus users of the state to work with Hazus in a supported technical process and a user friendly GIS portal. This is up and running and has been given to FEMA's Mitigation Framework Leadership Group for considerations (Croope, 2017).

DelDOT has developed multiple projects and is collaborating with multiple state agencies. In addition, DelDOT has strong support from the state and upper-level leadership to the incorporation of resilience initiatives. However, DelDOT is facing many of the same challenges as other transportation agencies regarding guidance, standards, better policies, lack of sufficient budget, among other challenges, related to the incorporation of resilience practices at the planning, engineering, management, policy, and administration levels (Delaware Flood Avoidance Workgroup, 2016).

In addition, DelDOT emphasized the 3D approach the internal work related to risk and resilience is taking and how it better supports decision making by confirming assessments and trends. The 3D approach can be summarized by the following:

- The government approach: FEMA Hazus;
- The academic/scientific approach: currently working with the University of Delaware on a few projects; and
- The market approach: re-insurance industry modeling approach (Croope, 2017).

Many of the existing models today still have a great level of uncertainty; DelDOT emphasizes the importance to "support data-based-decision making plus professional experts input" (Croope, 2017).

Port Authority of New York and New Jersey Case Example

PANYNJ has developed and implemented resilient practices in different areas of the agency, including planning, engineering, operations, and policy as well as at different modes (e.g., transit, port, highway, aviation). Information for the PANYNJ Port Department's resilience initiatives was obtained through an interview with Stephan Pezdek, senior project manager for port planning, resiliency, and sustainability, and Bethann Rooney, assistant director, both from the Port Department. Further information for other agency departments is based on a literature review and published sources. The case example summarizes the work and contributions done not only by PANYNJ's Port Department but also by the overall agency in terms of the implementation of resilience practices.

The PANYNJ is a bistate agency that oversees the design, building, operations, and maintenance of key infrastructure for the transportation network of the New York City (NYC)

metropolitan region, which includes New York and New Jersey. PANYNJ is a multimodal agency that oversees 31 major facilities including two tunnels, four bridges, six airports, five marine terminals and ports, two major bus stations/terminals, two rail systems, and the World Trade Center (Adams, 2015). The Port Authority has different departments that vary vastly in terms of the type of assets to maintain and operate as well as population served. One of the major PANYNJ departments is the Port Department. This department operates as a landlord port, where most of their tenants manage their own equipment and facilities. However, it is the Port Department's responsibility to maintain the roadways, a large share of the railway infrastructure, water, sewage, stormwater, snow removal, and a number of other portions of the infrastructure that support the tenant operations. The Port Department is a freight, maritime, and transportation function of PANYNJ. The type of assets that the Port Department maintains is vastly different than some of the other Port Authority departments, such as Port Authority Aviation, PATH, and tunnels and bridges, which includes public transit and bridge and tunnel functions. The reach and effect of the Port Department is to over 127 million people in the United States and Canada. The Port Authority is responsible for only the waterways at their facilities (Pezdek and Rooney, 2017).

These important transportation facilities have been exposed to multiple natural and human-made hazards: The terrorist attack of 9/11 (2001), Hurricane Irene (2011), and Hurricane Sandy (2012) are some of the events that have caused major damages. New York had over 60 major disaster declarations since 1954, including Superstorm Sandy, and 22 emergency declarations since 1974, most related to flooding, hurricanes, severe storms, and high tides, followed by winter storms and terrorist attacks (U.S. Department of Homeland Security, Online, b). Similarly, New Jersey has had over 30 major disaster declarations since 1955 and 11 emergency declarations since 1974, with most related to flooding, hurricanes, severe storms, and high tides (U.S. Department of Homeland Security, Online, b). In recent years, the States of New York (NYS) and New Jersey as well as NYC, have introduced resilience, sustainability, and environmental practices into their policies and guidance to reduce the effects from these types of events.

Some of New York's and New Jersey's resilience efforts include the creation of the NYS Resilience Institute for Storms and Emergencies (NYS RISE), Climate Change in NYS Projections (ClimAID), Community Risk Reduction and Resiliency Act, Climate Smart Resiliency Planning assessment tool, Sustainable Jersey Resiliency Program, New Jersey's Coastal Community Vulnerability Assessment and Mapping Protocol, and Getting to Resilience: A Coastal Community Resilience Evaluation Tool.

One of the first resilience initiatives in NYC was initiated by the release of a long-term sustainability plan called PlaNYC (currently OneNYC), which was initiated in 2007 by the Bloomberg administration in response to the city's long-term challenges, including change in climate conditions and aging infrastructure. To help accomplish the goals outlined in PlaNYC, the City's mayor organized the first New York City Panel on Climate Change (NPCC) in 2008. The NPCC was composed of a body of leading climate and social scientists and risk management experts to give advice on issues related to climate change and adaptation. It produced a set of climate projections specific to NYC. In January 2013, following Hurricane Sandy, the second NPCC (NPCC2) was convened, and a report was published to provide up-to-date scientific information and analyses on climate risks for use in the Special Initiative for Rebuilding and Resiliency (New York City Panel on Climate Change, 2013). NPCC2 was followed by NPCC3 in a January 2015 publishing of the NPCC latest report: *Building the Knowledge Base for Climate Resiliency: New York City Panel on Climate Change 2015 Report* (The New York Academy of Sciences, 2015). The latest report provides climate change projections through 2100; new coastal flood risk maps; enhanced dynamic flood inundation modeling, including effects of sea-level rise; and a process for enhancing the city's resilience indicators and monitoring systems (City of New York, 2015b).

Followed by the updates of NCPP and PlaNYC, different commissions have been created to evaluate key vulnerabilities of the city's critical infrastructure, including energy, transportation, land use, insurance, and infrastructure finance. Recommendations made related to the transportation sector include the following (NYS 2100 Commission, 2012):

- Developing a risk assessment of the city's transportation infrastructure;
- Strengthening existing transportation networks;
- Expanding transportation networks to increase redundancy; and
- Creating enhanced guidelines, standards, policies, and procedures.

Based on these projections and models, the city was identified to be vulnerable not only to flooding from storm events and sea-level rise but also to heat waves, heavy downpours, and severe drought (City of New York, 2015b).

Along with New York's and New Jersey's resilience efforts, the Port Authority has also developed their own resilience and sustainability policies for over 20 years.

Figure 18 presents some of the most important timeline of policies, guidelines, and initiatives that reflect New York's, New Jersey's, NYC's, and PANYNJ's resilience efforts.

In July 2006 PANYNJ issued Administrative Instruction 45-2 (AI-45-2) in order "to reduce adverse environmental impacts of the design, construction, operation and maintenance and occupancy or leasing of new or substantially renovated buildings and facilities, reconstruction projects, and programs" (The Port Authority of NY & NJ, 2011). Because of these policies, a series of sustainable design guidelines and frameworks were created to help the agency meet the requirements of AI-45-2. Port Authority and tenants are required to implement the *Sustainable Building Guidelines* on capital projects, and Port Authority is required to implement the *Sustainable Infrastructure Guidelines* (The Port Authority of NY & NJ, 2011 and 2017).

In 2015, a new set of guidelines was established to address climate impacts such as increased precipitation, temperature, severe storms, and sea-level rise for all Port Authority's capital projects and includes a stepwise process for building flood resilience. These guidelines are captured in PANYNJ's *Engineering Department Manual* as the Climate Resilience Design Guidelines and are divided into two primary sections: climate resilience and flood resilience. The first section provides an overview of future climate conditions in the region and offers examples of how agency infrastructure could be modified to increase resilience specific to climate change (The Port Authority of NY & NJ, 2009 and 2015). The design guidelines also establish the flood protection criteria for projects and describe a series of 10 steps to follow by engineers and architects to increase the flood resilience of assets. These steps include

1. Identify flood risks to project scope,
2. Determine the influence of any area or systemwide strategy,
3. Identify if project is part of an emergency plan or enterprise risk plan,
4. Review current codes,
5. Determine funding source requirements/guidelines,
6. Identify critical infrastructure,
7. Determine life expectancy,
8. Determine flood protection level,
9. Perform benefit–cost analysis, and
10. Establish flood resilience criteria.

PANYNJ also evaluated the vulnerability of its infrastructure to a range of climate change events, specifically to sea-level rise, storm surges, increased precipitation, and higher temperatures. Currently, the Port Department has identified areas where climate change might affect their infrastructure and systems and have taken steps to reduce the risk of future damage of

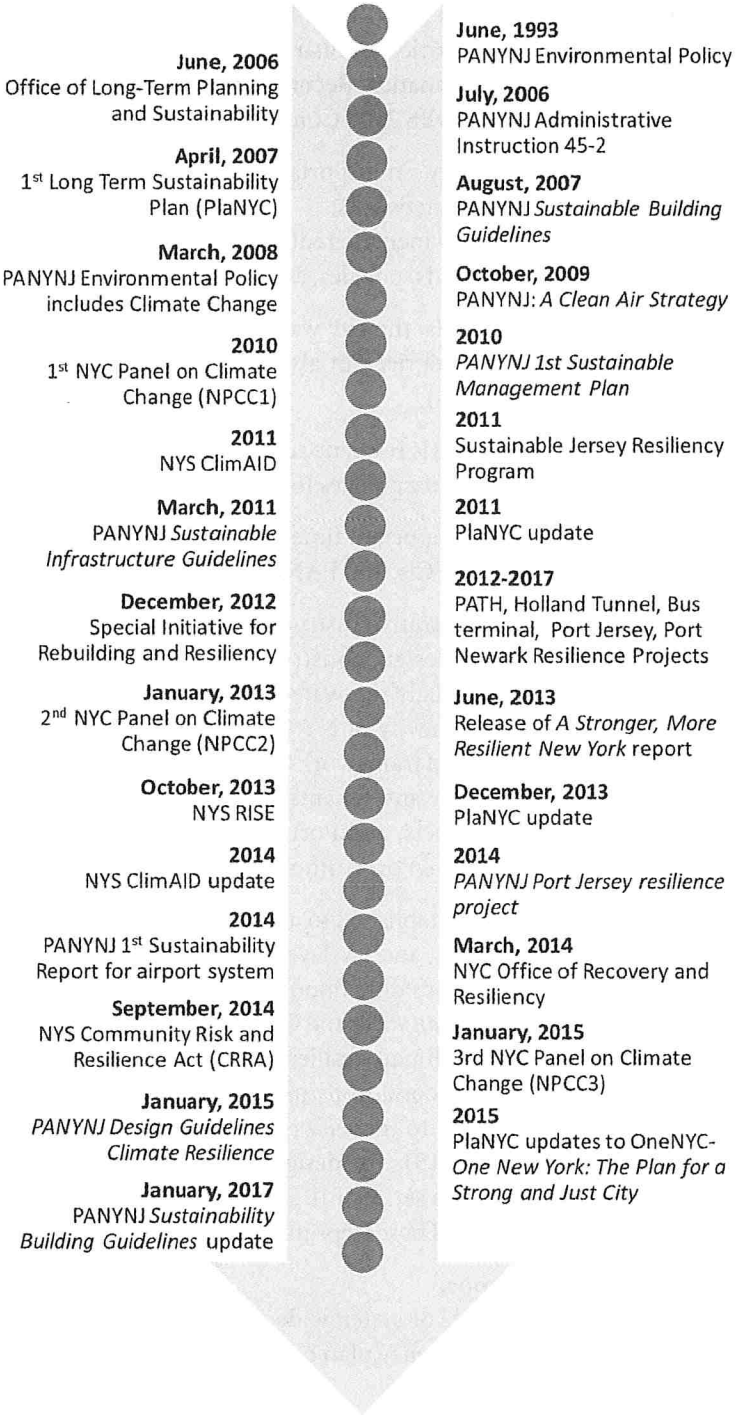

Figure 18. New York and PANYNJ resilience timeline.

their facility by elevating critical infrastructure, relocating equipment, wet-proofing applicable systems, and investing in systems to reduce system vulnerabilities. This has been in line with the PANYNJ's resiliency guidelines (Pezdek and Rooney, 2017).

To assess the long-term vulnerabilities of the agency's infrastructure to climate impacts, the Port Authority used the 50th percentile projections completed by the NPCC3, as recommended by the Office of Energy and Environmental Programs. These projections are generally applicable

to a 100-mile radius around the NYC metropolitan area and are used as the benchmark for PANYNJ's resilience guidelines (Pezdek, 2016). PANYNJ analyzed climate-related vulnerability and level of risk for a wide variety of agency infrastructure, including airports, marine terminals, tunnels and bridges, rails, bus stations, and other facilities. The risk analysis was used to prioritize the highest risk assets and develop adaptation strategies for those assets. Furthermore, PANYNJ performed a quantitative and qualitative risk assessment based on the likelihood of particular threats during the asset's lifetime and the magnitude of the consequences of such events. The output of the analysis was used in a risk matrix and used for investment prioritization of adaptation projects in the immediate term.

One of the main lessons learned during the process of development vulnerability and risk assessment to the agency's infrastructure includes the importance of access to accurate data and information, including institutional knowledge. Accurate data were critical for vulnerability and risk analysis. In particular, reliable information in terms of asset topography and elevation was important to assess risks related to flooding caused by storm surges and sea-level rise and was used to develop more precise flood maps such as FEMA FIRMs.

Along with developing a risk assessment, PANYNJ has developed an adaptation program to increase the agency's infrastructure resilience, putting in place a wide variety of adaptation strategies. The adaptation program includes security, climate change, operational, and physical adaptation projects. This program includes internal projects as well as collaboration with other external agencies in the state. Some of the internal projects include asset inventory, multihazard risk assessments, creation of new sustainable design guidelines, and physical and operational projects, among others. In addition, PANYNJ has collaborated on climate change and sustainability projects with other state agencies, organizations, and projects such as NPCC, NY State Sea-Level Rise Task Force, NY State Climate Action Council, and NY State ClimAID. Some of the challenges of the programs include funding and budgeting, policies and regulations, geographical and operational boundaries, and aging infrastructure, among others (Zeppie, Online).

PANYNJ continues with the investigation of processes to evaluate project priority on the basis of multihazard resilience metrics. The tunnels, bridges, and terminal department of PANYNJ investigated the development of a resilience management framework for critical agency infrastructure that focuses on resilience to all disruptions, incorporates lessons learned, and upgrades based on multiple hazards. Using DHS Science and Technology Directorate's risk and resilience methodologies, the Port Authority completed a pilot program in which these existing resilience management methodologies were applied to the Holland Tunnel and the Port Authority Bus Terminal to evaluate their vulnerability and resilience to flood and storms hazards (Valletta et al., 2015; NYS 2100 Commission, 2012).

In 2014, a pilot project led by FHWA was developed for the Port Jersey facility to study the effects of storm surge and the long-term effect of sea-level rise, specifically the effect to the facility's electrical system. There was an effort to map future inundation levels using the Hurricane SLOSH Model, FEMA, and sea-level maps. This pilot was one of the 10 engineering-based vulnerability assessments focused on transportation assets in the region and helped to better inform and set the agency's climate change resilience guidelines for planning, design, and operations (Pezdek, 2016).

Another effort developed as a partnership of the PANYNJ's Port Department, the Engineering Department, and the Office of Environmental and Energy Programs was the evaluation of the potential effect and risk of possible future storm events, as well as the effect of sea-level rise over the next 40 years, at their Port Newark South Peninsula facility. Some of the critical infrastructure under study included facility buildings, container terminal and storage, dry and liquid bulk, rail yards, and a warehouse. The risk assessment evaluated the likelihood that a given event

would affect an asset with a storm surge that would damage, destroy, or not affect that asset. To identify critical infrastructure and dependencies, an asset and operation database was developed using ArcGIS and web maps and later was integrated with heights to develop customized damage curves. Using USGS topographic data and FEMA flood insurance studies for still water elevations and starting wave conditions, an overland wave assessment and analysis was performed. The FEMA GIS-based model, Hazus, was used to determine the general cost effects to the different facilities including buildings and operational components. Some mitigation efforts, studied specifically at the port facilities, included the protection of electrical infrastructure and data centers, among other options (Pezdek, 2016).

Other projects at the Port Authority systems included the reconstruction and flood mitigation at some of its airports. La Guardia, Teterboro, Newark Liberty, and John F. Kennedy airports were affected by Superstorm Sandy and are part of the agency's Flood Mitigation and Storm Resilience Program (Transportation Resiliency Program) (New York State Governor's Office, Online). In 2014, PANYNJ published the first sustainability report covering the Port Authority's airport system, including a chapter on resilience. This chapter provides an overview of the airports' vulnerability to floods, sea-level rise, and storms associated with the effects of climate change (The Port Authority of NY & NJ, 2014).

In addition, PANYNJ has implemented resilience projects at their train system (PATH). The PATH system (tunnels, stations, and substations) was also severely damaged after Superstorm Sandy, causing failure to the power traction system, signals, elevators, escalators, and other electrical devices not only from flooding but also from salt intrusion and corrosion. The recovery effort after the storm event was mainly focused on the assets that were damaged during the event, however, further mitigations incorporate resilience practices to future climate conditions based on the new design guidelines (Adams, 2015).

As part of the OneNYC Plan, the Mayor's Office of Recovery and Resiliency developed an interactive map with the resiliency and recovery projects in the city, including PANYNJ resiliency projects (OneNYC).

The results from the agency's and city's vulnerability and risk assessments help the Port Authority to make better decisions in terms of adaptation options, which might include elevation, relocation, protection, or adaptation. In order to incorporate resilient practices into the agency at the project scoping, planning, design, construction, and operations levels, there has been extensive collaboration among different teams of experts, such as engineers, planners, emergency management, security personnel, and operations (DesRoches and Murrell, 2014).

In addition to the assessment of infrastructure resilience, PANYNJ is also looking at developing better operational plans for alternative methods of moving goods, supplies, and materials during emergencies when Port Authority infrastructure and facilities such as roads, rails, airports, and ports might be at risk or compromised. The Port Authority is sharing the results of the pilots with its tenants to be able to study not only the effects to their facilities but also the regional operations and incorporate the results into business planning (Pezdek, 2016).

Genesee Transportation Council Case Example

As mentioned previously, many state DOTs are including, or are beginning to include, the concept and practice of resilience into their agencies. However, not only are state DOTs incorporating these practices but also many transportation MPOs are developing vulnerability and risk assessments, developing climate change scenarios, and studying the resilience of their systems and assets, making resilience an important part of their transportation plans.

The Genesee Transportation Council (GTC) was chosen as an example of an MPO that has participated in a case example to incorporate resilience initiatives into their agency using FHWA's Vulnerability Assessment Framework. The information in this case example was gathered and compiled from published resources.

GTC is the MPO for the Genesee–Finger Lakes Region (Greater Rochester region) in upstate New York. The region consists of nine counties with a highway and bridge network of 27,000 lane miles of roads and approximately 1,600 bridges that carries over 30 million vehicle miles per day. The surface transportation network in the region is of vital importance for the movements of freight of major metropolitan areas, including New York City, Chicago, and Toronto.

GTC is responsible for transportation policy, planning, and investment decision making in this region, and its mission is to "maximize the contribution of the transportation system to the social and economic vitality of the Genesee–Finger Lakes Region." GTC is also responsible for producing and maintaining the Long Range Transportation Plan (LRTP) 2035, the Unified Planning Work Program, and the Transportation Improvement Program, among other mandated activities and programs (Genesee Transportation Council, 2016a, 2016b, 2017a, and 2017b).

As mentioned previously in the PANYNJ case example, NYS has experienced many disaster declarations due to the effects of major natural and manmade disasters. As a consequence of these catastrophic events, the state, its DOT, and its MPOs have been changing the way they plan, design, construct, operate, and maintain their infrastructure and systems. In order to evaluate and improve the resilience of their transportation system and infrastructure, and after the New York State 2100 Commission's recommendations for developing a risk assessment for the state's transportation infrastructure, GTC initiated a project to develop the first regionwide vulnerability assessment for the Genesee–Finger Lakes Region (NYS 2100 Commission, 2012). This project aligned with the state infrastructure program outlined in 2016 by Governor Cuomo, which established a $500 million extreme weather infrastructure hardening program to fund resilience projects to roadways that had been damaged by weather events. The GTC vulnerability assessment project was a collaborative effort among different stakeholders, including transportation, law enforcement, and emergency management. The project covered the nine counties in the region and had the major purpose of identifying systemwide and asset-specific strategies for hazard mitigation, including natural and manmade hazards, and proposed solutions for preventing or reducing the effects of such events. The vulnerability assessment included infrastructure such as roads (with functional classification of Minor Collector or greater), bridges (along regional roadway network), emergency response facilities, traffic and transit operation centers, highway garages, and fuel storage (Genesee Transportation Council, 2016a).

This assessment also builds on climate change adaptation initiatives as part of their regional sustainability plan (Bovenzi, 2015). The vulnerability assessment plays an important role in evaluating and improving the region's resilience, which is defined as the "ability to adapt to changing conditions and prepare for, withstand, and rapidly recover from disruption" with focus on "enhancing assets to a 'New Normal'" (Bovenzi, 2015). Figure 19 shows a representation of the GTC resilience view.

The GTC vulnerability assessment process has the following five major steps:

1. Identification of critical transportation assets with an inventory of the critical transportation assets across the Genesee–Finger Lakes Region and based on information collected from studies and evacuation plans and input from stakeholders.
2. Identification of natural and human-caused hazards, including a profile of hazard types and geographical extent based on historical records, emergency management and hazard mitigation plans, and stakeholder experiences.

Figure 19. GTC resilience diagram.

3. Understanding of consequences from threats to vulnerable and critical assets with the potential of occurrence.
4. Asset prioritization based on the critical transportation infrastructure vulnerability and developed using a Microsoft Excel scoring method joined with GIS data.
5. Development of strategies for preventing or mitigating the effects of the identified possible hazards (Genesee Transportation Council, 2016b).

Some of the natural hazards identified for the study include floods, winter weather, severe storms, landslides, seismic activity, sinkholes, extreme temperatures, and wildfire. In addition, the following human-caused hazards were also identified: structural failure, fire, hazardous material spills, roadway accidents, derailments, and sabotage/acts of terrorism. The vulnerability assessment was done on three geographical levels: macro (region), meso (municipality), and micro (neighborhood) (Bovenzi, 2015).

The vulnerability assessment is based on a qualitative analysis of the four key factors that define their system and asset vulnerability such as sensitivity of the asset, likelihood of the event, exposure of the asset to particular hazards, and the expected consequence or severity of the effect from such events. These four factors were each assigned scores from 1 to 5 and then added to calculate the total vulnerability score for each particular asset. The process to conduct the vulnerability assessment is based on the *FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework* (FHWA, 2012a). The assessment also uses concepts from other sources such as the outcome of two studies from the Volpe National Transportation Center named *Beyond Bouncing Back: A Roundtable on Critical Transportation Infrastructure Resilience* and *Infrastructure Resiliency: A Risk-Based Framework* (U.S. Department of Transportation, 2013).

The Genesee–Finger Lakes Regional Critical Transportation Infrastructure Vulnerability Assessment final report was published in June 2016 (Genesee Transportation Council, 2016a). In order to perform the assessment, multiple data sources were compiled, including GIS data from various agencies such as New York State Thruway Authority, NYSDOT, and GTC, among other emergency management and planning agencies. Some of the GIS data included asset location, flood maps (FEMA), and other hazard maps.

The hazard identification was county specific; however, it was identified that flooding, severe storms, and hazmat in transit spills were the hazards that pose a significant risk to critical transportation assets across the region (Genesee Transportation Council, 2016a). In addition, the number of assets identified by the assessment to have high or moderately high vulnerability include 20 bridges, 91 roadway segments, and 18 facilities (Genesee Transportation Council, 2016a).

Table 4. GTC Mitigation Strategies.

Key Themes	Categories
• Prevention • Protection • Redundancy • Recovery	• Planning and policy • Communication, education, and awareness • Infrastructure and construction • Natural and land resource protection • Operations and maintenance

In order to mitigate these hazards, GTC developed a hazard mitigation strategy toolbox and placed their strategies into four key themes and five categories. These themes and categories are presented in Table 4. The report provides a toolbox with a range of options for mitigation strategies for each one of the five categories to help agencies to identify possible mitigation strategies (Genesee Transportation Council, 2016a).

Along with the mitigation strategies, a table with potential funding sources is included to help implement these strategies; the funding sources vary from FEMA grants to the FHWA ER program.

The major goal of the GTC vulnerability assessment was the development of a process to prioritize investments on transportation infrastructure projects that help to increase the resilience of the region. In addition, it looks to provide an Excel tool that can be used by different agencies to update or customize their database in order to conduct more localized vulnerability assessments (Genesee Transportation Council, 2016a).

Some of the GTC lessons learned during the vulnerability assessment process include the importance of

- Interagency and intermunicipal partnership and coordination,
- Integration of the vulnerability and risk assessment into the transportation infrastructure investment decision-making process, and
- Integration of the vulnerability assessment findings into the land use and policy decision-making process.

The GTC vulnerability assessment project was featured as one of FHWA's case studies on resilience planning (FHWA, 2016).

Summary

This chapter documented five case examples related to the incorporation of resilience practices by infrastructure agencies. The case examples were developed by using information from the survey, as well as in-depth interviews with staff. The case examples included information from the following agencies:

- ADOT,
- CDOT,
- DelDOT,
- PANYNJ, and
- GTC (MPO).

The three state DOTs included in the case examples began resilience analysis from different starting points. Two of the states were involved in FHWA climate change pilots and have continued their efforts beyond the pilots, and one state suffered a significant loss from a flood event that prompted the agency to begin a proactive assessment of system resilience.

ADOT was involved in the FHWA climate change pilots and has focused efforts on establishing a unique relationship with USGS to improve understanding of the potential flow and path of extreme rain events and how those flows may affect ADOT assets. CDOT is building on lessons learned from the devastating 2013 flood event, which damaged over $750 million in highway assets alone. Using the ASME RAMCAP Plus framework, CDOT is proactively conducting an all-hazards risk and resilience assessment of the I-70 corridor from border to border. DelDOT has focused their efforts on incorporating resilience into their policies and planning areas. Much of the focus of their resilience assessments is focused on sea-level rise and coastal flooding given the state has the lowest average elevation in the country and 381 miles of shoreline. While ADOT is seeking candidate sites for implementation of the information being generated by USGS and their resilience investment economic analysis process, CDOT is taking a systematic look at a specific corridor, I-70, and analyzing all applicable hazards on the corridor through their pilot project. DelDOT, being a coastal, low-lying state, has focused much of their attention on proactive identification of flood-prone areas and incorporating resilience into their planning and policies.

The case example developed for PANYNJ demonstrates how resilience can be incorporated into design policies. The development of guidelines to address climate impacts such as increased precipitation, temperature, severe storms, and sea-level rise provide an approach for state DOTs to begin to include such requirements in their design guides.

The GTC vulnerability assessment project was a collaborative effort among different stakeholders, including transportation, law enforcement, and emergency management. The project covered the nine counties in the region and had the major purpose of identifying systemwide and asset-specific strategies for hazard mitigation, including natural and manmade hazards, and proposed solutions for preventing or reducing the effects of such events.

Similar lessons learned from the case examples include the need for buy-in from management to support resilience analysis, the need for a range of staff to be engaged in assessments, reaching out to nontraditional partners to capitalize on needed and unique data and modeling capabilities, and seeking low-hanging opportunities to demonstrate the value of resilience assessment. Each of the highlighted agencies has experienced extreme weather events in recent years that may have contributed to leadership support; however, dedicated staff within each agency who seek to know more, to proactively manage better, have begun to benefit from lessons learned from recent events, which should help these agencies absorb, rebound, and recover more efficiently from future events.

CHAPTER 6

Conclusions

Summary

The focus of this project was to better understand how resilience is being addressed by transportation agencies in their planning, engineering, operations management, policy, and administrative actions. The information provided detailed the evolution of policies that promote highway resilience, definitions of risk and resilience and the relationship between these two concepts, and how agencies are incorporating resilience practices through project development, policy, and design. The information contained in this report was gathered through three primary sources: a literature review, a survey of state DOTs, and five case examples developed through interviews with infrastructure agencies incorporating resilience into their programs.

The literature review was concentrated on the evolution of policies from risk identification and management toward understanding and assessing system resilience, meaning the ability of a system to absorb and recover from events that disrupt normal operations. Efforts were also made to review a range of definitions of resilience within and outside of the transportation sector, and an effort was made to provide information on the relationship between risk and resilience to help clarify the two concepts. Next, efforts were made to document resilience metrics that have been developed within the transportation sector, and it was noted that many of the documented examples lack in their ability to capture the full range of the Rs of resilience. A review of a few indices that have been used to reflect resilience was provided, and the literature review concluded with a summary of frameworks that have been developed to help agencies begin to assess the resilience of their systems through detailed processes.

Next, the findings of a survey of 40 state DOTs were presented. Questions were developed to serve as a screening tool to identify agencies willing to participate in the case examples presented in chapter 5. Through the survey, information was gathered on the state DOTs' use of resilience in their various management areas; the resilience assessments that have been conducted and at what level; information on metrics being used; and most importantly, what information state DOTs are seeking to better assess system resilience.

Finally, five case examples were developed to demonstrate innovative approaches to resilience assessment and incorporation of resilient practices. The case examples were developed for ADOT, Colorado DOT, DelDOT, PANYNJ, and GTC. Each of the case examples reviewed the evolution of resilience analysis within each agency and included details on areas of application. Information also was included on changes to agency policy and procedures as related to resilience assessment. The case examples demonstrate various levels of maturity within the agencies for resilience assessment and capture the lessons learned from each agency with regard to resilience policy, modeling, inclusion in design standards and practice, and unique mechanisms being used to fund resilience practices.

Findings

A review of national policies found that while resilience policies are becoming well established, there is a lack of integrating resilience into practice within transportation. With the recent requirements for risk-based asset management plans, it is possible that state DOTs have yet to fully complete those requirements and are struggling to address capturing resilience within their management approach. There also has yet to be strong guidance developed on the relationship between risk and resilience, which would be helpful to allow agencies to understand how their risk assessments can help support their system resilience analyses. In addition, although policy touts the need for resilient systems, the lack of monetary assessment of the value of system resilience makes it challenging for agencies to stretch limited dollars in another direction when already faced with challenges related to new performance metrics such as safety, infrastructure health, and operational reliability. The relationship between each of these metrics and system resilience has not yet been fully flushed out in an easy-to-use guidance or modeling tool to assess resilience and reflect the relationship between mandatory performance metrics and resilience, so implementation will continue to be a challenge at state DOTs.

The literature review identified shortcomings in the definition of resilience, the quantitative relationship between risk and resilience, and metrics to measure resilience. Much of the focus of resilience definitions is on the ability to recover post event; however, a DHS study was reviewed that helped to define key discriminators for resilience definitions to address the full range of time periods in which resilience is needed to be addressed by asset managers and owners and reflect four goal areas (maintaining continuity of function, graceful degradation, recovery of function to desired function in designated time, and inhibiting basic state of change). The reflection of definitions against the key discriminators provided by DHS for infrastructure systems may be of use to state DOTs as they move forward with their resilience programs as a way to help identify resilient practices and policies that address a broader range of activities that can be implemented to provide more than quick recovery post event to transportation assets.

Resilience metrics also appear to be lacking in quantitative measures that can be readily calculated and assessed. Much of the published peer-reviewed literature focuses on using existing operational metrics normally related to system reliability as surrogates to reflect recovery time as a measure of system resilience. Some researchers have attempted to measure characteristics such as the angle of deterioration and recovery triangles during weather events on interstate systems. This approach appears to have promise with the availability of historical traffic performance data at the micro- and meso-scales. In general, however, it appears that agencies are struggling to measure system resilience, as was reflected in the state survey reviewed in chapter 4 of this report.

The survey of state DOTs revealed that most respondents are working to incorporate resilience into their management programs; however, a closer look at their response to questions related to information needed revealed that agencies are seeking information on resilience metrics and assessment methods, criticality assessment models, asset vulnerability, and the expected benefits from mitigation measures. Given the lack of documented metrics for resilience in the literature review and the request of additional data from states on how to measure and assess resilience, this appears to be a pressing need to fully address resilience in transportation systems.

Conclusions

Based on the information gathered through three distinct sources of data (literature review, state DOT surveys, and case examples), the three primary challenges for state DOTs for incorporating resilience into their management programs appear to be the following:

- A lack of understanding of how resilience is related to risk assessment;
- A lack of metrics to measure system resilience and the benefits expected from resilience investments; and
- A lack of clear direction as to how system resilience can affect mandated transportation performance measures such as safety, infrastructure condition, and system operations and vice versa.

Much of the information related to highway system resilience appears to be disjointed in that climate change, risk assessment, asset deterioration as reflected in asset management plans, operational performance, and safety performance have yet to be fully integrated to demonstrate how each affects the other. In addition, the lack of clear metrics to measure system resilience leaves agencies to struggle to implement resilient practices. Finally, data to support such analyses, such as the expected performance or benefit derived from mitigation measures implemented to improve system resilience, make it difficult for agencies to justify investments as compared to model and data-rich areas such as operational or safety performance when competing from the same limited pool of funding. Simply stating that a design or maintenance activity will improve system resilience will not go very far in the funding allocation process when other management areas have well-established data sets, metrics, and models to forecast expected performance. National research could address these shortcomings to further advance the integration of resilient practices into highway programs.

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Glossary

Adaptation: An adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects.

Asset (transportation system): Essentially any feature built and maintained on a highway (e.g., pavement, bridge, culvert, sign, and embankment).

Asset management: A data-driven, strategic approach for the preservation, rehabilitation, and maintenance of assets.

Climate change: Any significant change in the measures of climate lasting for an extended period of time. Climate change includes major variations in temperature, precipitation, or wind patterns, among other environmental conditions, that occur over several decades or longer. Changes in climate may manifest as a rise in sea level as well as an increase in the frequency and magnitude of extreme weather events now and in the future.

Consequence: The outcome of an event occurrence, including immediate, short-, and long-term, direct and indirect losses and effects.

Consequence mitigation: The planned and coordinated actions or system features designed to reduce or minimize the damage caused by attacks or natural hazard events.

Countermeasures: What is in place, or could be put in place, to reduce the vulnerability of an asset and the probability that an attack will succeed in causing a failure or significant damage.

Critical asset: An asset that if lost or damaged would severely degrade or curtail an owner's ability to perform core functions or its mission.

Extreme weather events: Weather events that can include significant anomalies in temperature, precipitation, and winds and can manifest as heavy precipitation and flooding, heatwaves, drought, wildfires, and windstorms (including tornadoes and tropical storms). Consequences of extreme weather events can include safety concerns, damage, destruction, and economic loss. Climate change can also cause or influence extreme weather events.

Preparedness: The actions taken to plan, organize, equip, train, and exercise to build, apply, and sustain the capabilities necessary to prevent, protect against, ameliorate the effects of, respond to, and recover from climate change–related damages to life, health, property, livelihoods, ecosystems, and national security.

Redundancy: A measure of alternative routes available.

Sustainability: The capacity to endure. The goal of sustainability can be described with the triple bottom line, which includes giving consideration to three primary principles: social, environmental, and economic.

SLOSH	sea, lake, and overland surges from hurricanes
SoVI	Social Vulnerability Index
TAMP	Transportation asset management plans
TAZ	Transportation analysis zones
TER	Transportation Economic Resilience
TOSE	Technical, organizational, social, and economic
TSSR	Transportation System Security and Resilience
TRB	Transportation Research Board
UN	United Nations
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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